Plant Uptake of Selenium from Soils Overlying Unmined Sedimentary Rock Units and Potential Use Of These Soils as Capping Materials for Revegetated Waste Rock Dumps

Cheryl L Mackowiak[1] and Michael C Amacher[2]

[1] University of Florida
North Florida Research and Education Center
155 Research Dr
Quincy FL 32351-5677
850-875-7126
CLMackowiak@ifas.ufl.edu

[2] USDA-FS Rocky Mountain Research Station
Forestry Sciences Lab
860 N 1200 E
Logan UT 84321
435-755-3560
mamacher@fs.fed.us

Background:

The phosphate rock mining industry removes topsoils and subsoils overlying phosphate rock ore units during the mining process and stores these soils in stockpiles. Industry and land management agencies would like to use this soil resource on top of waste rock dumps containing seleniferous waste shale as capping material that can be revegetated to minimize plant uptake of Se and thus protect grazing animals from exposure to potentially toxic levels of Se.

Phosphatic shales are enriched in Se and other trace elements. In general, Se concentrations in phosphatic shale decrease with increasing degree of alteration (i.e., weathering) of the shale (Herring and Grauch 2004). A significant fraction of the Se in phosphatic shale is water soluble (Herring 2004) and is available for plant uptake (Mackowiak et al. 2004). Perkins and Foster (2004) found that that most of the Se in unweathered rocks of the Meade Peak Member of the Permian Phosphoria Formation is associated with the sulfide fraction with lesser amounts in organic matter and oxyhydroxide fractions and as elemental Se. In contrast, most of the Se in weathered rocks is found in the oxide fraction with lesser amounts in the organic matter fraction and as elemental Se. Thus, as mineral sulfide weathering progresses, Se is released and re-incorporated into the weathered metal oxide fractions. Although, the bioavailability of Se in each of its solid phase forms in phosphatic shale is largely unknown, some Se released during metal sulfide weathering is available for plant uptake.

The high degree of Se availability for plant uptake from phosphatic shale + soil mixtures (Fig. 1) led Mackowiak and Amacher to recommend that phosphatic shales that come into contact with plant roots on re-vegetated waste rock dumps should contain no more than 1 mg/kg total Se to keep plant Se concentrations below the 5 mg/kg recommended limit for forages (Food and Nutrition Board 1980).

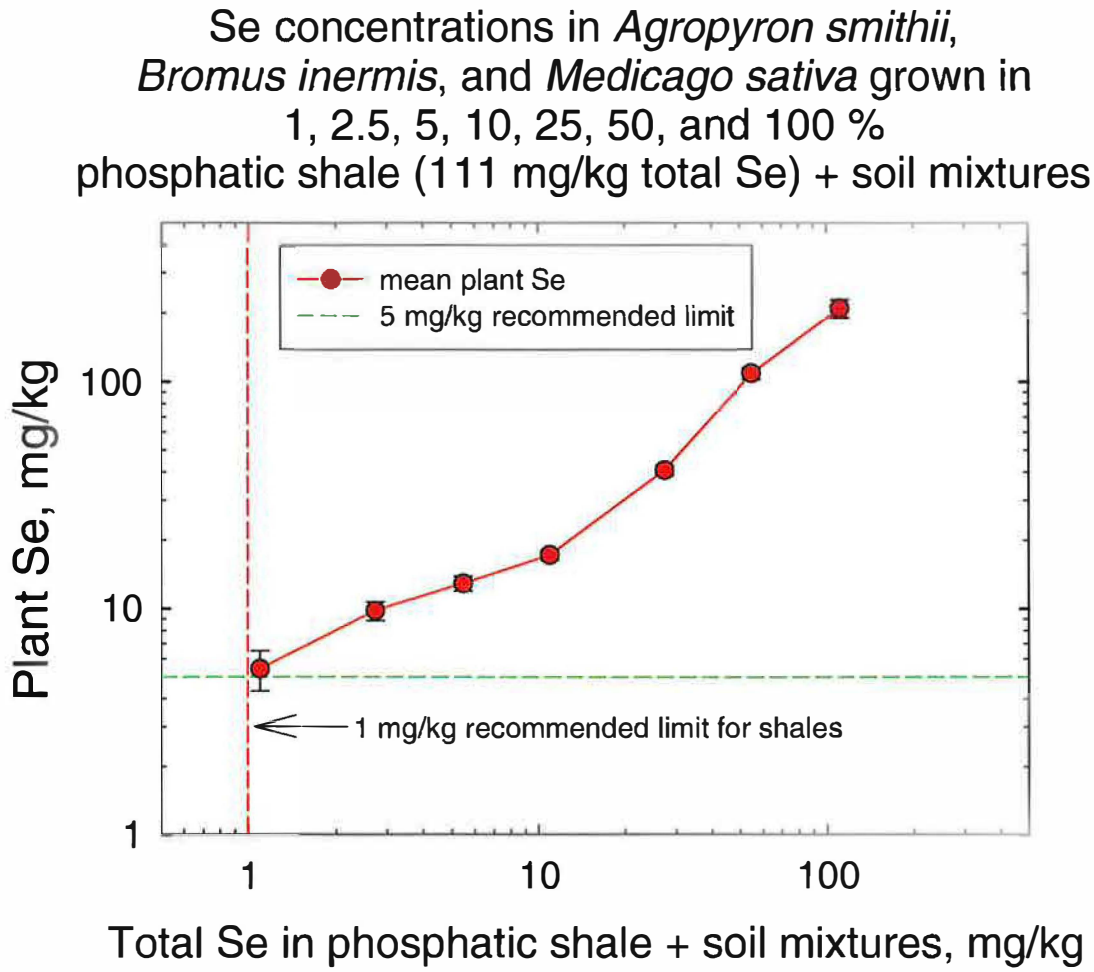

Se concentrations in Agropyron smithii, Bromus inermis, and Medicago sativa grown in 1, 2.5, 5, 10, 25, 50, and 100 % phosphatic shale (111 mg/kg total Se) + soil mixtures
mean plant Se
5 mg/kg recommended limit
1 mg/kg recommended limit for shales
Plant Se, mg/kg
100
10
1
1
10
100
Total Se in phosphatic shale + soil mixtures, mg/kg

Fig. 1. Mean ± standard error Se concentrations in *Agropyron smithii*, *Bromus inermis*, and *Medicago sativa* grown in phosphatic shale (111 mg/kg total Se) + soil mixtures containing 1, 2.5, 5, 10, 25, 50, and 100 % phosphatic shale. Symbols are the mean of 12 values (3 plant species x 4 replicates). A recommended limit of 1 mg/kg total Se in phosphatic shale to keep plant Se concentrations below 5 mg/kg is shown as a vertical dashed red line.

Amacher et al. (2001) found that soils overlying the sedimentary rock units that comprise the Phosphoria Formation (Wells limestone or Grandeur Tongue dolostone, Meade Peak phosphatic shale, and Rex chert) contain far less total Se than waste rock dump materials and the sedimentary rocks of the Phosphoria Formation (Herring and Grauch 2004). They proposed a conceptual model to account for Se concentrations, bioavailability, and potential for mobilization as a function of chemical weathering and degree of disturbance of the sedimentary rock units (Table 1). Unweathered shale with high concentrations of Se have the greatest potential for Se mobilization once these deposits are disturbed via mining and placed in waste rock dumps subject to surficial weathering processes, whereas more weathered soils developed over sedimentary rock deposits that have been disturbed by mining operations and subjected to increased

weathering would tend to have the least potential for further mobilization of any residual Se. If degree of weathering is related to depth, then degree of weathering would tend to decrease and Se concentrations and bioavailability would tend to increase with depth (Fig. 2).

Table 1. Relationship of weathering and disturbance history of phosphatic shales, related sedimentary deposits, and overburden soils to potential for Se mobilization.

	Weathering history & tendency →					
Disturbance history	Unweathered	Lightly weathered	Moderately weathered	More strongly weathered	↓	Potential for Se mobilization
Undisturbed	Deeper phosphatic shale deposits	Near-surface sedimentary deposits[1]		Soil developed over sedimentary deposits		
Older disturbances		Old waste rock dumps		Old soil stockpiles[2]		
Recently disturbed	New waste rock dumps			New soil stockpiles[2]		
	← Potential for Se mobilization					

[1] Grandeur dolostone, Rex chert, etc.
[2] Old and new soil stockpiles are topsoil and subsoil overburden removed during phosphate rock mining and stockpiled for use in waste rock dump reclamation. New soil stockpiles have been recently removed from their original position on the landscape and stockpiled in a new weathering environment. Old soil stockpiles are those that have been subjected to weathering for at least several years.

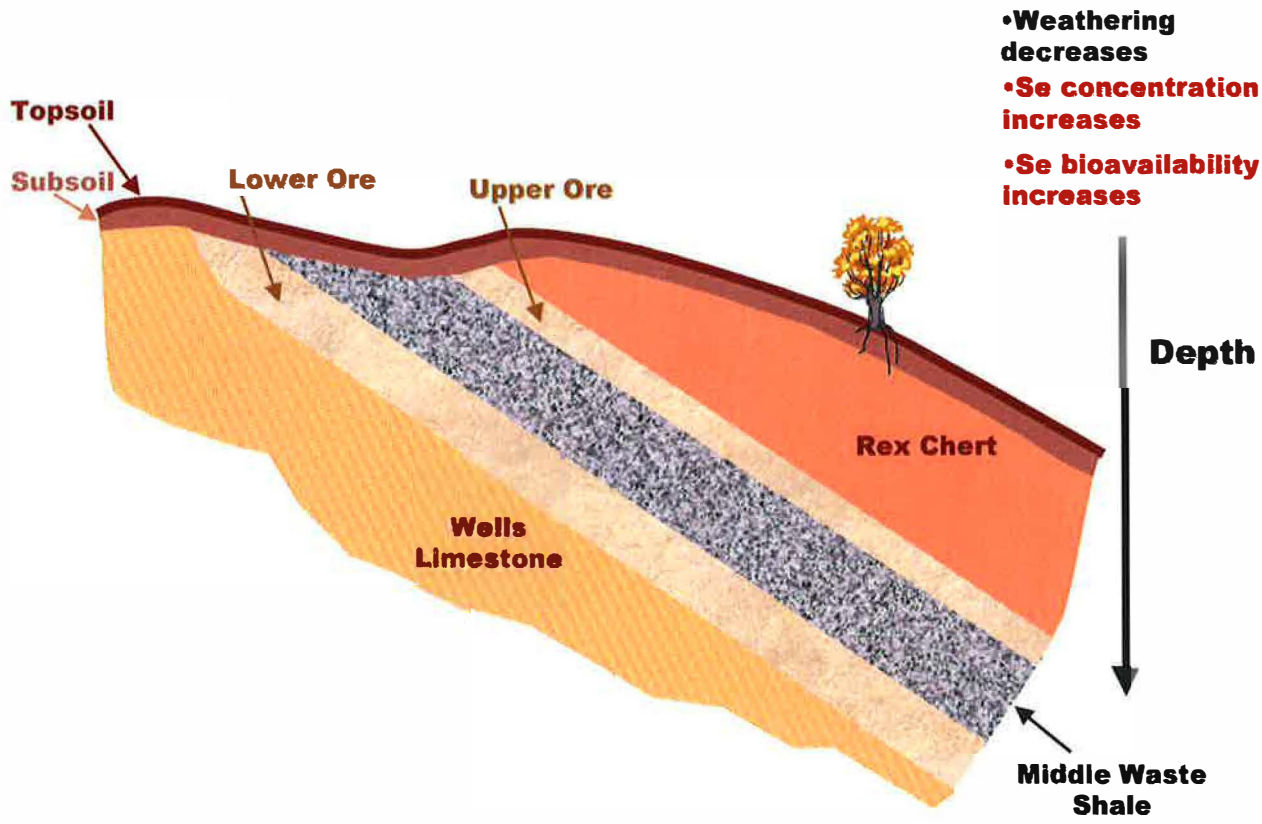
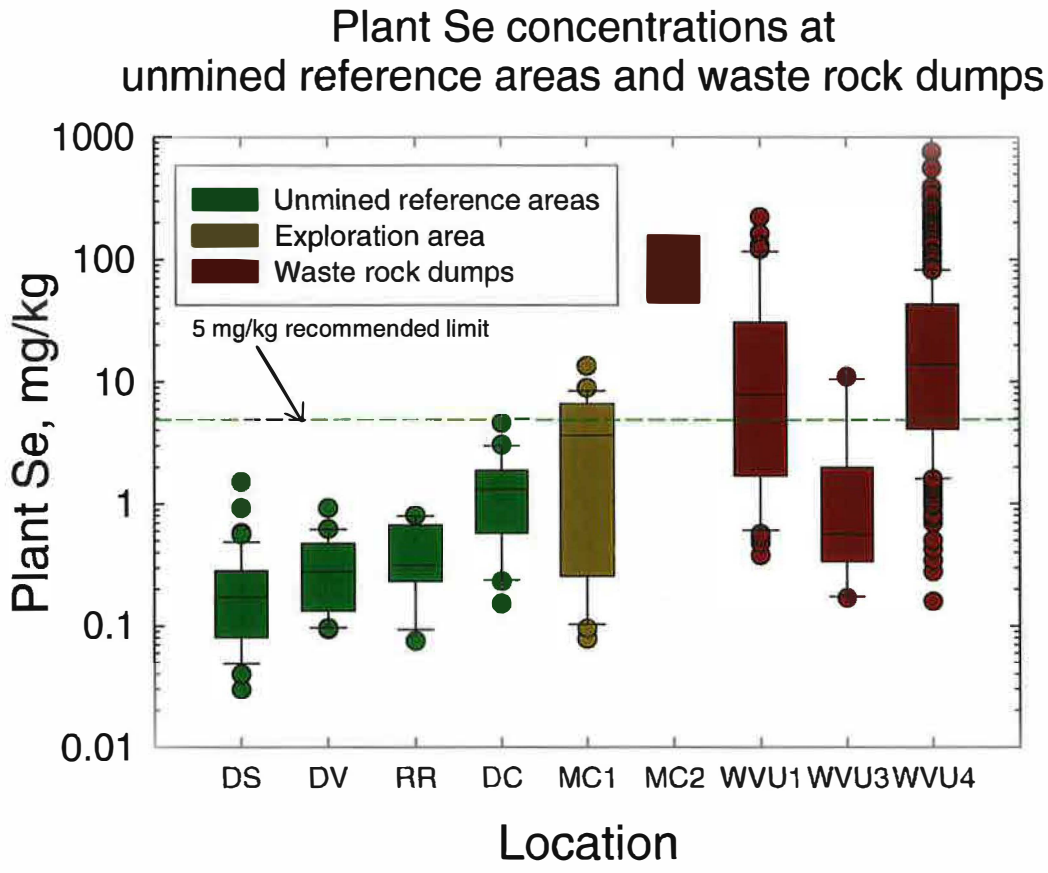


Fig. 2. Cross-section diagram of sedimentary rock units and expected changes in extent of physical and chemical weathering and Se concentrations and bioavailability with depth.

Soils are an excellent capping material for establishing plant communities on waste rock dumps because of their relatively high nutrient, organic matter, and soil biota content compared to waste rock, but they should be used only if their bioavailable Se content is low enough to keep plant Se concentrations below the 5 mg/kg recommended limit for forages (Food and Nutrition Board 1980). Because soils represent the most weathered portion of the surficial geologic environment, residual Se in soils overlying the sedimentary rock units that comprise the Phosphoria Formation would tend to be less soluble and hence less available for plant uptake than Se in the sedimentary rock units.

Mackowiak et al. (2004) verified the hypothesis that Se in soils developed over Phosphoria Formation sedimentary rock units was less available for plant uptake than Se in the sedimentary rock. They found that there was far less Se uptake by plants growing in undisturbed or partially disturbed soils developed over the sedimentary rock units (unmined reference area soils in Fig. 3) than in plants growing on dumps consisting of waste rock from the sedimentary rock units (Fig. 3). These results reflect both degree of weathering (less weathered sedimentary rocks in waste rock dumps

versus more weathered soils over sedimentary rocks) and disturbance history (undisturbed soils over sedimentary rocks versus highly disturbed waste rock dumps containing sedimentary rocks).



DS = Dairy Syncline lease area
DV = Dry Valley
RR = Rasmussen Ridge
DC = Deer Creek
MC1 = Maybe Canyon exploration area above old collapsed adit
MC2 = Maybe Canyon waste rock dump
WVU1 = Wooley Valley unit 1 waste rock dump
WVU3 = Wooley Valley unit 3 waste rock dump
WVU4 = Wooley Valley unit 4 waste rock dump

Fig. 3. Box plots of plant Se concentrations at unmined reference areas (Dairy Syncline, Dry Valley, Rasmussen Ridge, and Deer Creek), a partially disturbed exploration area above an old collapsed adit (Maybe Canyon 1), and severely disturbed waste rock dumps (Maybe Canyon 2, Wooley Valley units 1, 3, and 4). The 25th and 75th percentiles are shown as a box around the median (50th percentile), the 10th and 90th percentiles are shown as error bars and the 5th and 95th percentiles and outliers are shown as points.

Even though soils that developed over sedimentary rock units tend to contain far less Se than the sedimentary rocks because chemical weathering has resulted in Se being leached from the soil, the residual Se in the soils may become available for plant uptake if the soil is disturbed by mining operations and subjected to increased weathering in soil stockpiles or as a cap over waste rock dumps. To investigate the plant availability of Se in soils over Phosphoria Formation rocks, Mackowiak and Amacher (2003) grew *Agropyron smithii*, *Bromus inermis*, and *Medicago sativa* in pots containing 4 soils from Dry Valley, ID (2 topsoils and 2 subsoils) with different total Se levels (0.8, 1.4, 3.4, 12.4 mg/kg total Se). They found that despite disturbing the soils three times (collection before the glasshouse experiment, sieving and mixing each soil before seeding, and breaking-up, re-mixing, and re-seeding each soil after 3 plant harvests), plant Se concentrations remained far below the 5 mg/kg recommended limit for forages for all 7 plant cuttings and despite re-disturbing and re-planting the soils (Fig. 4). They concluded that soils with total Se concentrations below 13 mg/kg could be safely used as vegetated capping material over waste rock dumps.

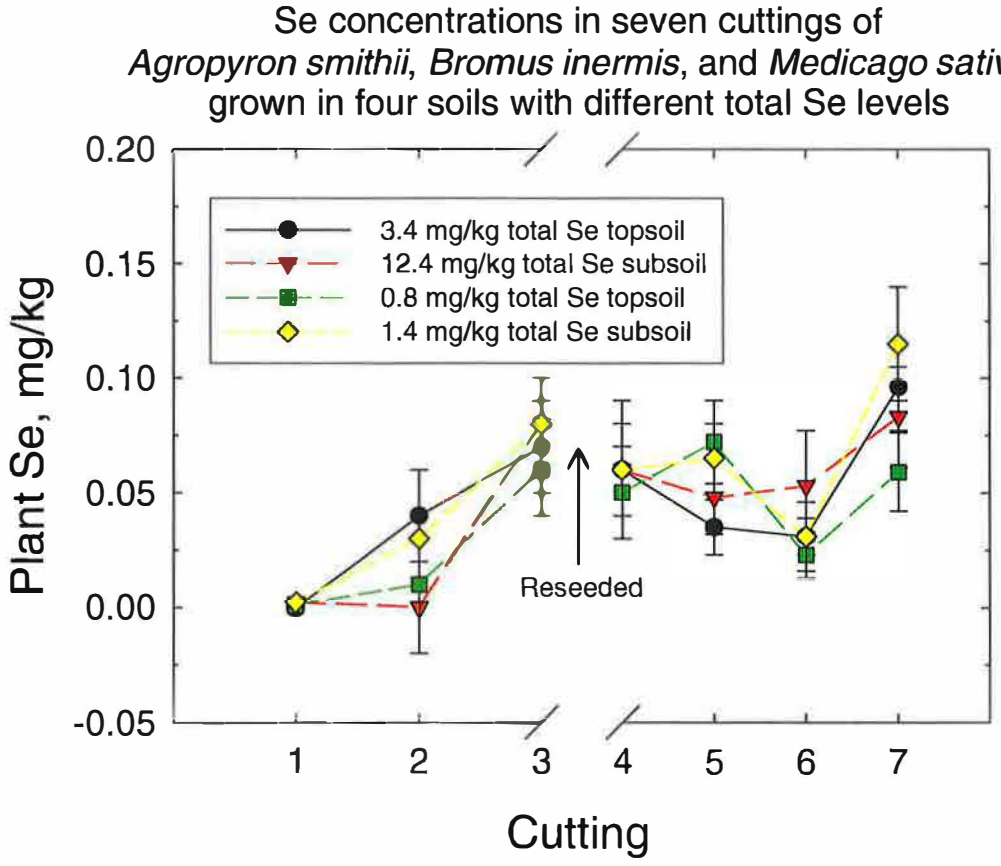
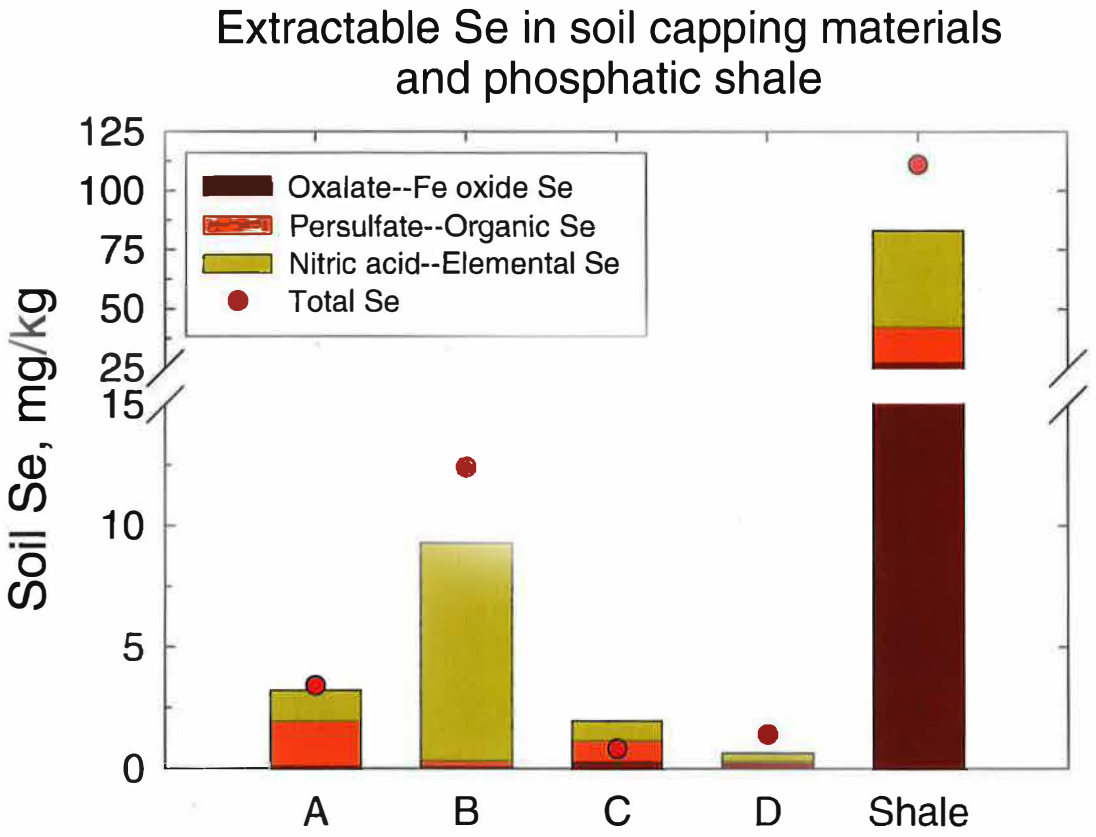


Fig. 4. Se concentrations in 7 cuttings of *Agropyron smithii*, *Bromus inermis*, and *Medicago sativa* grown in 4 soils from Dry Valley (2 topsoils and 2 subsoils) with different total Se levels. Symbols are the mean of 12 values (3 plant species x 4 reps) and standard errors are shown as error bars. After cutting 3 (year 1), soils were air-dried, broken apart (re-disturbed), and re-seeded; and 4 more cuttings were collected (year 2).

The low plant availability of residual Se in weathered soils as compared to phosphatic shale is also reflected by the low amounts of oxalate-extractable Se in the Dry valley soils compared to phosphatic shale from Maybe Canyon (Fig. 5). Oxalate extracts non-crystalline Fe oxides and associated Se, which is assumed to be more available for plant uptake than organic forms of Se extractable by persulfate and elemental Se extractable by nitric acid (Fig. 5). These results suggest that oxalate may have some value in evaluating capping materials for plant available Se. The upper limit for total Se in soils developed over sedimentary rock units to maintain plant Se levels below 5 mg/kg remains unknown until soils with higher total Se concentrations are tested for plant uptake.



A = 3.4 mg/kg total Se topsoil
B = 12.4 mg/kg total Se subsoil
C = 0.8 mg/kg total Se topsoil
D = 1.4 mg/kg total Se subsoil
Shale contains 110 mg/kg total Se

Fig. 5. Oxalate, persulfate, and nitric acid extractable Se in 4 Dry Valley soils (2 topsoils and 2 subsoils) with different total Se levels and Maybe Canyon phosphatic shale. Oxalate extracts non-crystalline Fe oxides and associated Se, persulfate extracts organic Se, and hot nitric acid extracts elemental Se.

Selenium concentrations in plants from unmined reference areas were first reported in Mackowiak et al. (2004). Only a few plant samples from an old exploration area upslope from an old collapsed adit at Maybe Canyon were found to have Se concentrations in excess of the 5 mg/kg recommended limit (MC-1 labeled box plot in Fig. 3). However, plant samples from old exploration trenches at Dairy Syncline and Deer Creek did not exceed 5 mg/kg, although one plant sample from Deer Creek was close to the 5 mg/kg limit (DC box plot in Fig. 3). Because exploration activities such as trenches partially disturb the soils overlying the sedimentary rock units, it is possible that these types of disturbances may have increased exposure of sedimentary rocks to weathering and thus ultimately increased plant uptake of any oxidized Se. Thus, we planned additional sampling of plants and soils over the undisturbed Phosphoria Formation above the exploration area above the collapsed adit at Maybe Canyon.

Total Se in unmined reference area soils at Dairy Syncline was first reported in Amacher et al. (2001). Soil samples were also collected at unmined reference sites at Deer Creek, Rasmussen Ridge, and Maybe Canyon, but these results have not yet been reported and relationships between oxalate-extractable or total Se in soils overlying sedimentary rock units at unmined references areas and Se concentrations in vegetation growing in these soils have not been examined.

Objectives:

- To determine Se concentrations in plant species growing in soils overlying sedimentary rock units in unmined reference areas.
- To determine oxalate-extractable and total Se in soils overlying sedimentary rock units in unmined reference areas including undisturbed sites and old exploration trenches.
- To determine the relationships, if any, between plant Se concentrations and oxalate-extractable and total Se in soils overlying sedimentary rock units at unmined reference areas.
- To re-examine the 13 mg/kg recommended limit for total Se in soils used as capping material by considering new data from unmined reference areas.

Methods:

Soil and plant samples were collected from unmined reference areas at Dairy Syncline lease area (1999 and 2001), Deer Creek lease area (2000), Rasmussen Ridge (2001), and Maybe Canyon (2001 and 2002). Approximate locations of these areas are shown in Fig. 19-1 in Mackowiak et al. (2004). Originally, these unmined areas were sampled to provide comparisons of plant and soils in undisturbed baseline or reference areas to plants and soils on highly disturbed waste rock dumps. Details of plant and soil sampling and analysis are presented in Mackowiak and Amacher (2003) and Mackowiak et al. (2004).

At each site, transects were established across the Meade Peak member of the Phosphoria Formation. For most transects, one end (random start) was established over the Wells limestone (or Grandeur Tongue dolostone) and the other end was over the Rex chert. Sampling locations along each transect were at equal intervals or were

selected based on the presence of representative vegetation in each area. Distances along each transect were measured with a hip-chain or measuring tape anchored with a chaining pin. Latitudes and longitudes of each sampling point and transect starting points were recorded with a GPS unit.

Plant sample collection, preparation and analysis:

The above-ground portion of each sampled plant species was clipped and placed in labeled paper bags and taken to the lab for pre-analysis preparation. Samples of plant species that could not be identified in the field were also collected and returned to the lab for identification using various plant taxonomy manuals. A list of plant species sampled in unmined reference areas and waste rock dumps is given in table 19-1 in Mackowiak et al. (2004) and the plant species list for the unmined reference areas only is shown in Table 2.

Table 2. Plant species sampled at unmined reference areas.

Scientific name	Abbreviation	Common name	Lifeform
Agropyron canimum	AGCA	Bearded wheatgrass	Grass
Agropyron smithii	AGSM	Western wheatgrass	Grass
Agropyron spicatum	AGSP	Bluebunch wheatgrass	Grass
Deschampsia caespitosa	DECA	Tufted hairgrass	Grass
Elymus cinereus	ELCI	Great Basin wildrye	Grass
Elymus glaucus	ELGL	Blue wildrye	Grass
Phleum pratense	PHPR	Common timothy	Grass
Carex hoodii	CAHO	Hood sedge	Sedge
Carex rossii	CARO	Ross sedge	Sedge
Achillea millefolium	ACMI	Western yarrow	Forb
Balsamorhiza sagittata	BASA	Arrowleaf balsamroot	Forb
Epilobium angustifolium	EPAN	Fireweed	Forb
Pedicularis racemosa	PERA	Sickletop lousewort	Forb
Medicago sativa	MESA	Alfalfa	Legume
Artemisia tridentata	ARTR	Big sagebrush	Shrub
Ceanothus velutinus	CEVE	Snowbrush, buckbrush	Shrub
Symphoricarpos oreophilus	SYOR	Mountain snowberry	Shrub
Populus tremuloides	POTR	Aspen	Tree

The plant samples were dried in mechanical convection ovens at 60 C for 48 h and ground to <20-mesh in a Willey mill before digestion. Plant samples collected in 1999 and 2000 were analyzed by the USGS lab in Denver, CO (Herring and Amacher, 2001). Selenium was determined by hydride atomic absorption spectrophotometry (HG-AAS). Plant samples collected in 2001 and 2002 were analyzed by the Soil and Water Analysis Lab at the Forestry Sciences Lab, USDA-FS-RMRS, Logan, UT. The HNO_3 + H_2O_2 digestion method of Jones (1989) was used to digest the samples. Selenium in the digests was determined by HG-AAS. To convert oxidized Se in the digests to Se(IV) for hydride analysis, equal volumes of digest and concentrated HCl were heated

for 20 min at 80 C in a graphite block digestor. Conversion efficiency was monitored by carrying a Se(VI) standard through the procedure. Also, several digest samples were spiked with known amounts of Se(IV) and Se(VI) and carried through the Se species conversion procedure. Plant digestion and analysis repeatability was monitored by including a sample of prepared *Medicago sativa* (alfalfa) from Wooley Valley unit 4 waste rock dump with each group of plant samples to be analyzed. Reagent and method blanks, calibration standards, and check samples were also included as part of the lab QA/QC procedures.

Soil sample collection, preparation, and analysis:

At Dairy Syncline in 1999, Deer Creek in 2000, and Maybe Canyon in 2001 and 2002, 0 – 10 cm soil samples were collected at each sampling location using a 5-cm diameter bucket auger. The Dairy Syncline transects were re-sampled in 2001 using a 5-cm diameter impact-driven soil coring sampler to collect 0 – 10 and 10 – 20 cm soil cores. One of the Dairy Syncline transects (transect 4) was established along the base of the vertical cut of an old exploration trench and in 1999 and 2001, soil samples were collected from the exposed subsoil near the base of the trench. At Rasmussen Ridge in 2001, a vertical cut in the hillslope was made with a bulldozer to expose a complete soil profile from the soil surface down to the parent material consisting of the upper and lower ore and middle waste sedimentary rock units. Plant samples were collected from the undisturbed area near the top of the vertical cut by running a sampling transect parallel to the exposed vertical soil profile. Vertical soil sampling transects were established above the upper and lower ore zones and upper and lower middle waste shale zones by anchoring a tape measure at the soil surface at the top of the exposed soil profile and letting the tape hang freely to the bottom of the vertical cut. Soil cores were collected at intervals along each vertical profile using an impact-driven soil core sampler (5-cm diameter x 10-cm depth). Sampling points were selected so that each exposed major stratigraphic unit (delineated by geomorphology) was sampled.

All soil samples were air-dried at ambient temperature and sieved (after crushing aggregates) through a 2-mm stainless steel sieve to remove coarse fragments. Soil samples were further reduced in size to <100 mesh by rolling them for 48-hr with steel pins in glass scintillation vials on a roller table.

To determine total recoverable Se, a 0.500-g subsample of each soil was digested in 20 mL of a 3.5:1 mixture of concentrated HNO_3 + concentrated $HClO_4$ in glass digestion tubes in a graphite block digestor at 95 C (Amacher et al. 2001, Amacher 2003). Digestion was complete when the volume was reduced to <2 mL and fumes of $HClO_4$ were visible. The digests were diluted to 50 mL with deionized water prior to analysis. To convert oxidized Se in the digests to Se(IV) for hydride analysis, equal volumes of digest and concentrated HCl + 1 mL of 0.1 M potassium persulfate were heated for 20 min at 80 C in a graphite block digestor. Conversion efficiency was monitored by carrying a Se(VI) standard through the procedure. Also, several digest samples were spiked with known amounts of Se(IV) and Se(VI) and carried through the Se species conversion procedure. Digestion and analysis accuracy was verified by periodically analyzing three USGS sedimentary rock check samples collected,

prepared, and analyzed for the Western US Phosphate Project (Herring and Wilson 2001).

Oxalate-extractable Se was determined by shaking a 0.500-g subsample of each soil with 25.0 mL of 0.2 M ammonium oxalate + 0.2 M oxalic acid in a 125-mL wide-mouth screw-cap plastic jar for 2 hr and filtering the suspension through Whatman 40 filter paper to recover the extract. To convert all forms of Se in the extracts to Se(IV) for hydride analysis, equal volumes of digest and concentrated HCl + 1 mL of 0.1 M potassium persulfate were heated for 20 min at 80 C in a graphite block digestor.

Data analysis:

Relationships between plant Se and soil total Se were tested using various regression models including linear, exponential, and a two-segment linear model using various SAS procedures (Statistical Analysis Systems, Cary, NC).

Results and Discussion:

Dairy Syncline Lease Area:

All the plant Se concentrations from four transects across the Phosphoria Formation at the Dairy Syncline lease area were below the 5 mg/kg recommended limit for Se in forages (Fig. 6). These data were originally presented in Mackowiak et al. (2004) as medians and 25th and 75th percentiles of the Se concentrations in all the plant species. In Fig. 6, the Se concentrations are shown for each lifeform at each location across each transect. Selenium concentrations in the various lifeforms at all locations were not significantly different (Fig. 7). Only transect 2 had higher Se concentrations in plants growing in soil overlying the Meade Peak member of the Phosphoria Formation (Fig. 6). At the other three transects, plant Se concentrations were not influenced by the type of rock underlying the soils. Transects 3 and 4 were along the top and base of the vertical cut of an old exploration trench. Even though, the subsoil was exposed by the exploration trench, plants growing in this exposed subsoil did not have elevated levels of Se compared to plants in the soil along the top of the trench.

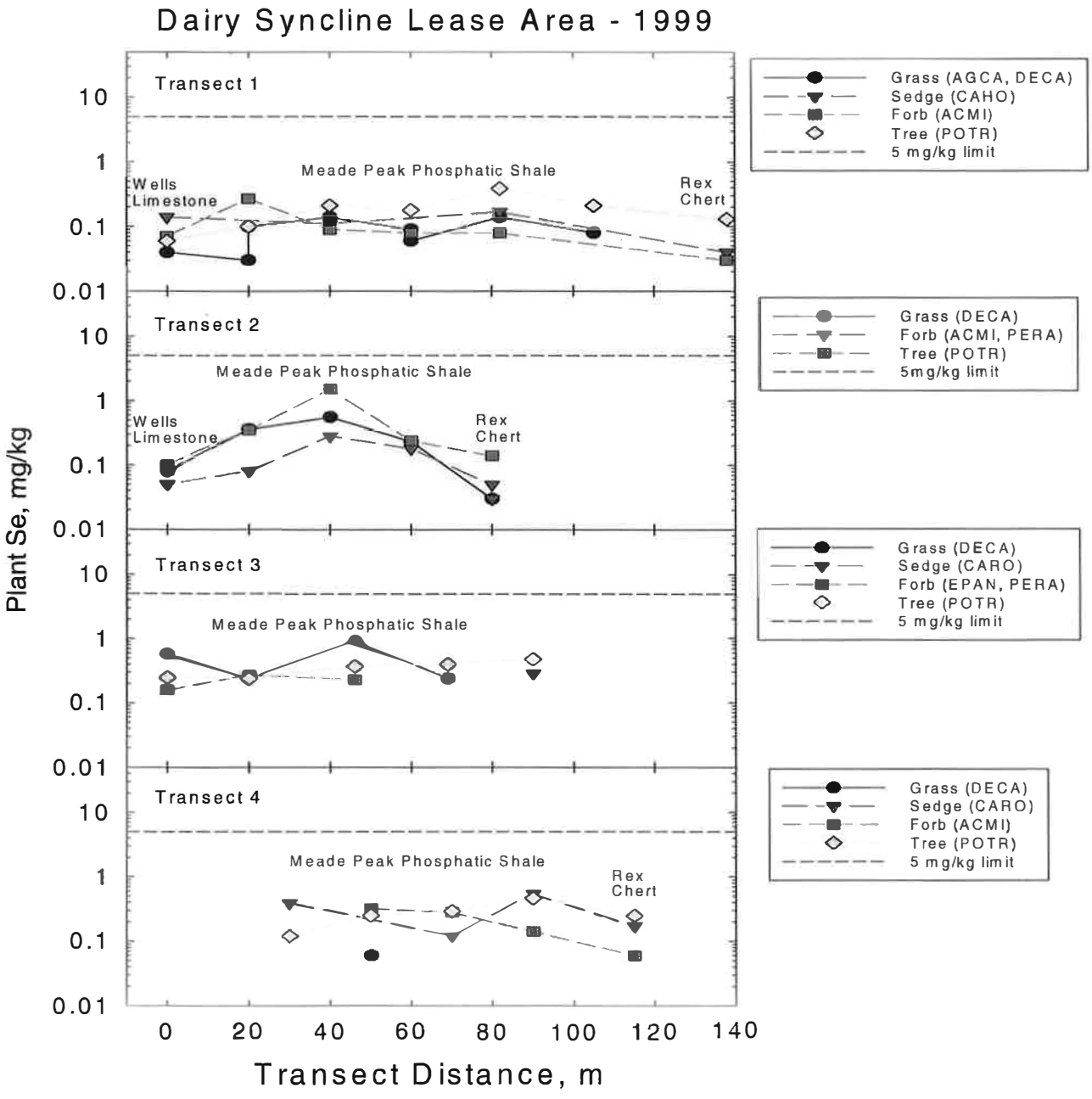


Fig. 6. Se concentrations in various plant lifeforms along transects across sedimentary rock units (Wells limestone, Meade Peak phosphatic shale, and Rex chert) at Dairy Syncline lease area in 1999. Transects 1 and 2 were at undisturbed sites, transect 3 was along the top of an old exploration trench, and transect 4 was along the base of the trench.

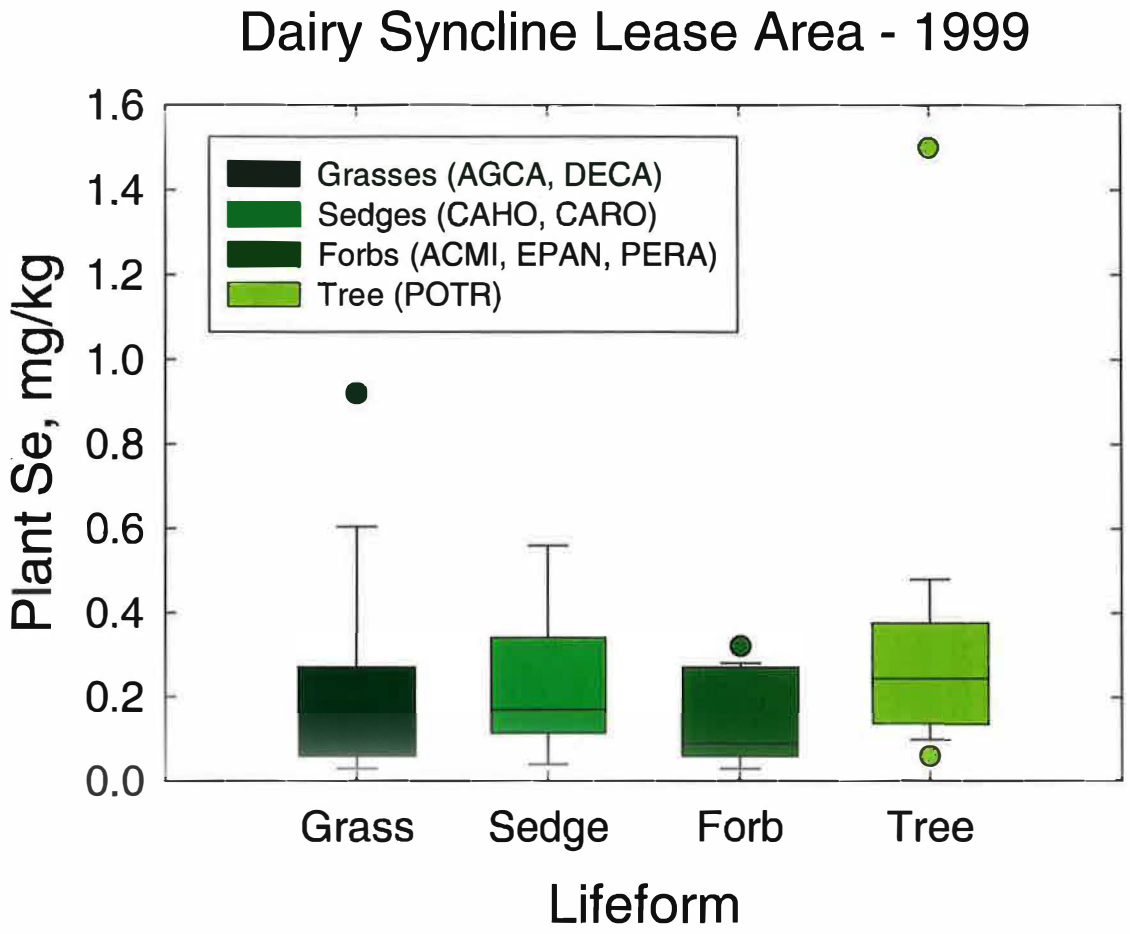


Fig. 7. Box plots of Se concentrations in various plant lifeforms along transects across sedimentary rock units (Wells limestone, Meade Peak phosphatic shale, and Rex chert) at Dairy Syncline lease area in 1999. The 25th and 75th percentiles are shown as a box around the median (50th percentile), the 10th and 90th percentiles are shown as error bars and the 5th and 95th percentiles and outliers are shown as points.

Although the trench was about 2-3 meters deep, there was no exposed dark-colored phosphatic shale. Soil depth to the sedimentary rock units is unknown at this location. Elevated levels of soil total Se were found in the subsoil at the base of the exploration trench as compared to the 0 – 10 cm soil samples of the other three transects (Fig. 8), but these subsoil total Se concentrations were still below the 13 mg/kg recommended limit for total Se in soil capping materials. Oxalate-extractable Se levels were very low (Fig. 8) and unrelated to soil total Se levels (Fig 9).

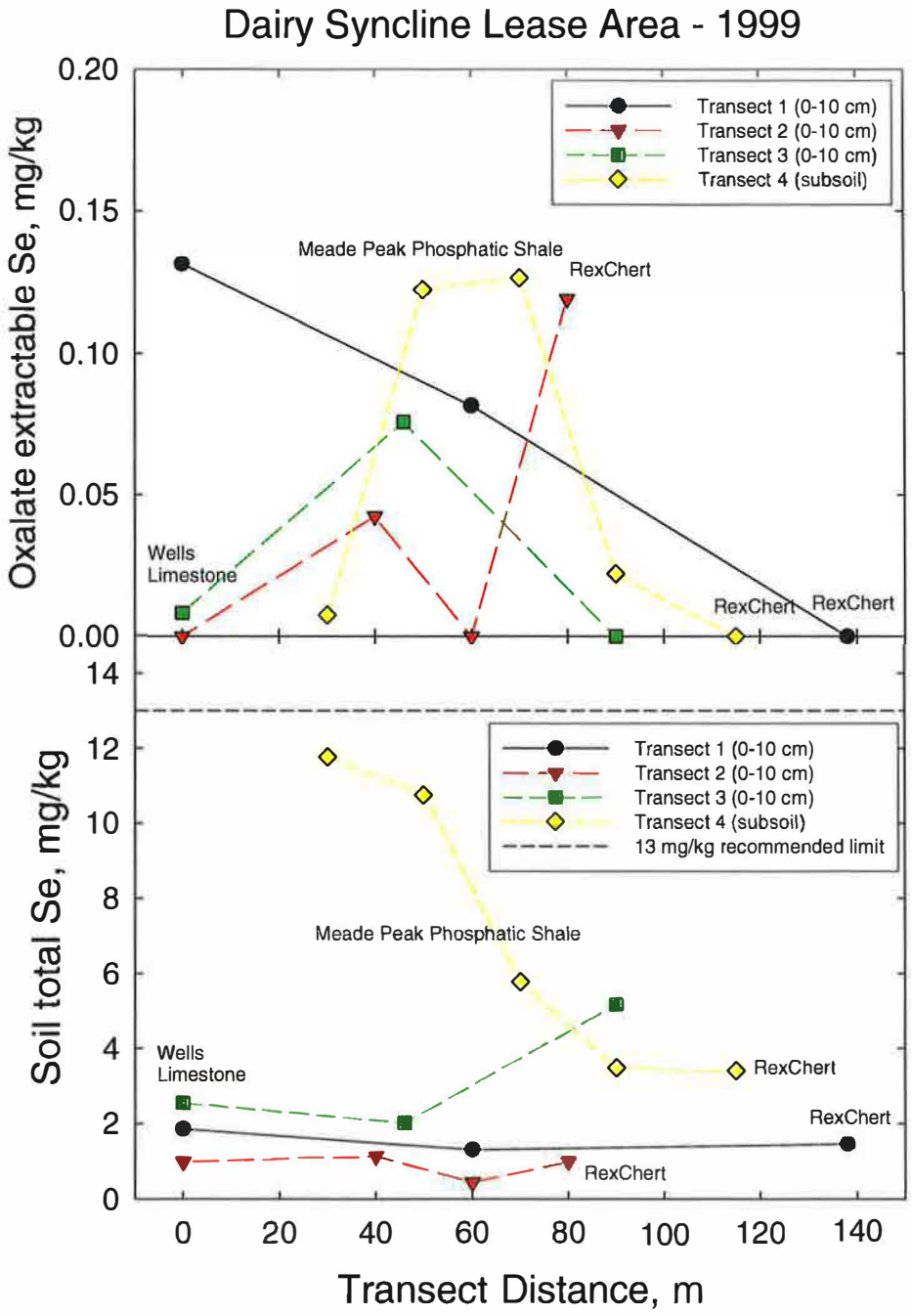


Fig. 8. Oxalate-extractable (top) and total Se (bottom) in 0-10 cm and subsoil soil samples collected along transects across sedimentary rock units (Wells limestone, Meade Peak phosphatic shale, and Rex chert) at Dairy Syncline lease area in 1999. Transects 1 and 2 were at undisturbed sites, transect 3 was along the top of an old exploration trench, and transect 4 was along the base of the trench in the weathered parent material.

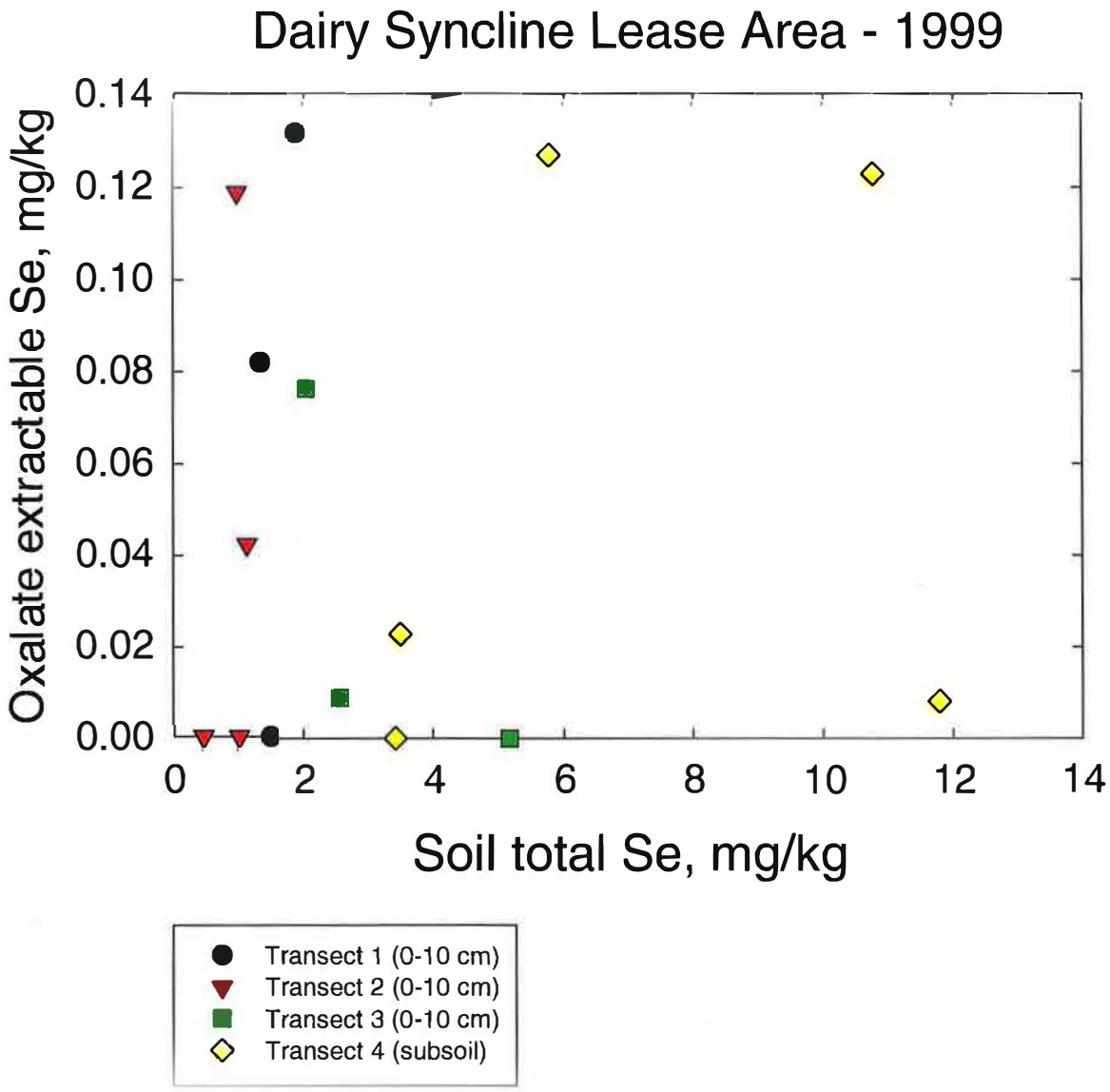


Fig. 9. Relationship between oxalate-extractable and total Se in 0-10 cm and subsoil soil samples collected along transects across sedimentary rock units (Wells limestone, Meade Peak phosphatic shale, and Rex chert) at Dairy Syncline lease area in 1999. Transects 1 and 2 were at undisturbed sites, transect 3 was along the top of an old exploration trench, and transect 4 was along the base of the trench in the weathered parent material.

A more detailed sampling in 2001 showed that oxalate-extractable Se in subsoil over the Meade Peak phosphatic shale at transect 4 was slightly higher than in the 0 – 10 and 10 – 20 cm soil cores from transect 3 (Fig. 10). Subsoil total Se (transect 4) was at or below the 13 mg/kg recommended limit and total Se in 10 – 20 cm soil cores was similar to that in 0 – 10 cm soil cores (Fig. 11). Oxalate-extractable and total soil Se in the 2001 soil cores did not show a significant relationship (Fig. 12). Although oxalate-extractable Se in the 1999 soil cores was not closely related to oxalate-extractable Se in

the 2001 soil cores (Fig. 13), total Se in the 1999 and 2001 soil samples were closely related (Fig. 14). There was some scatter in the subsoil data because of soil variability and the impossibility of sampling the exact the same location.

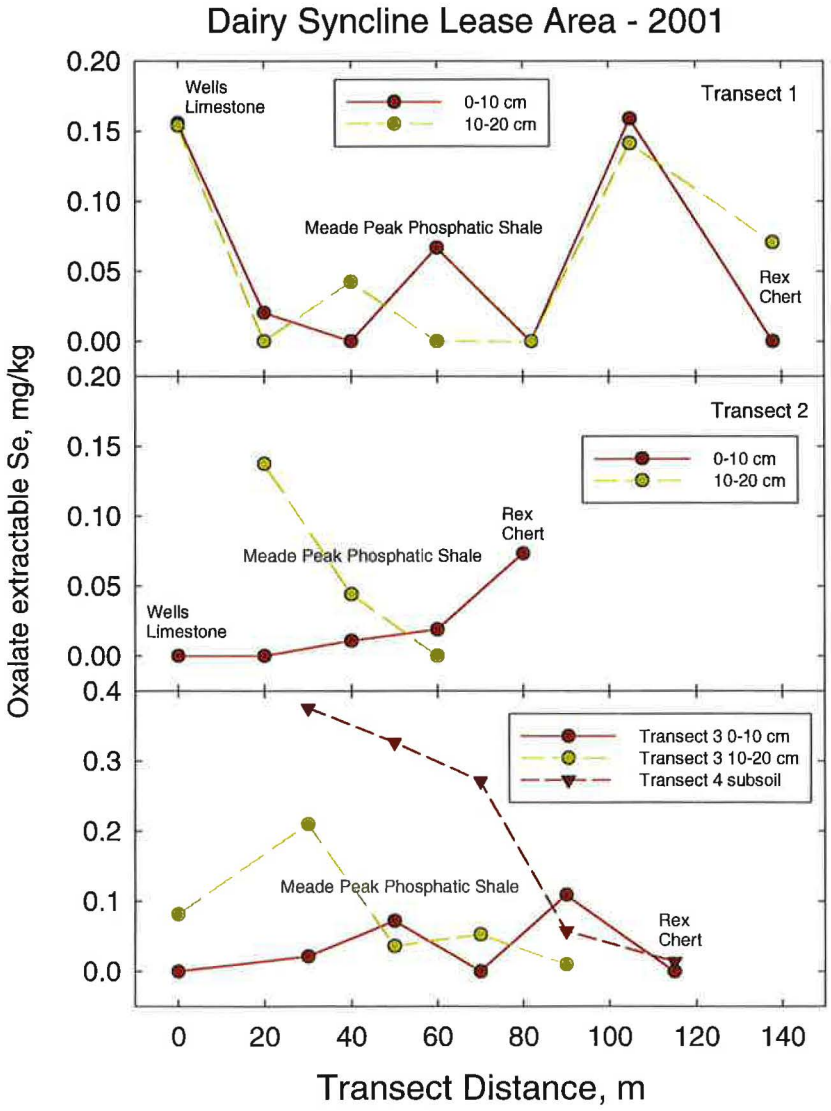


Fig. 10. Oxalate-extractable Se in 0-10 cm, 10-20 cm, and subsoil soil samples along transects across sedimentary rock units (Wells limestone, Meade Peak phosphatic shale, and Rex chert) at Dairy Syncline lease area in 2001. Transects 1 and 2 were at undisturbed sites, transect 3 was along the top of an old exploration trench, and transect 4 was along the base of the trench in the subsoil weathered parent material.

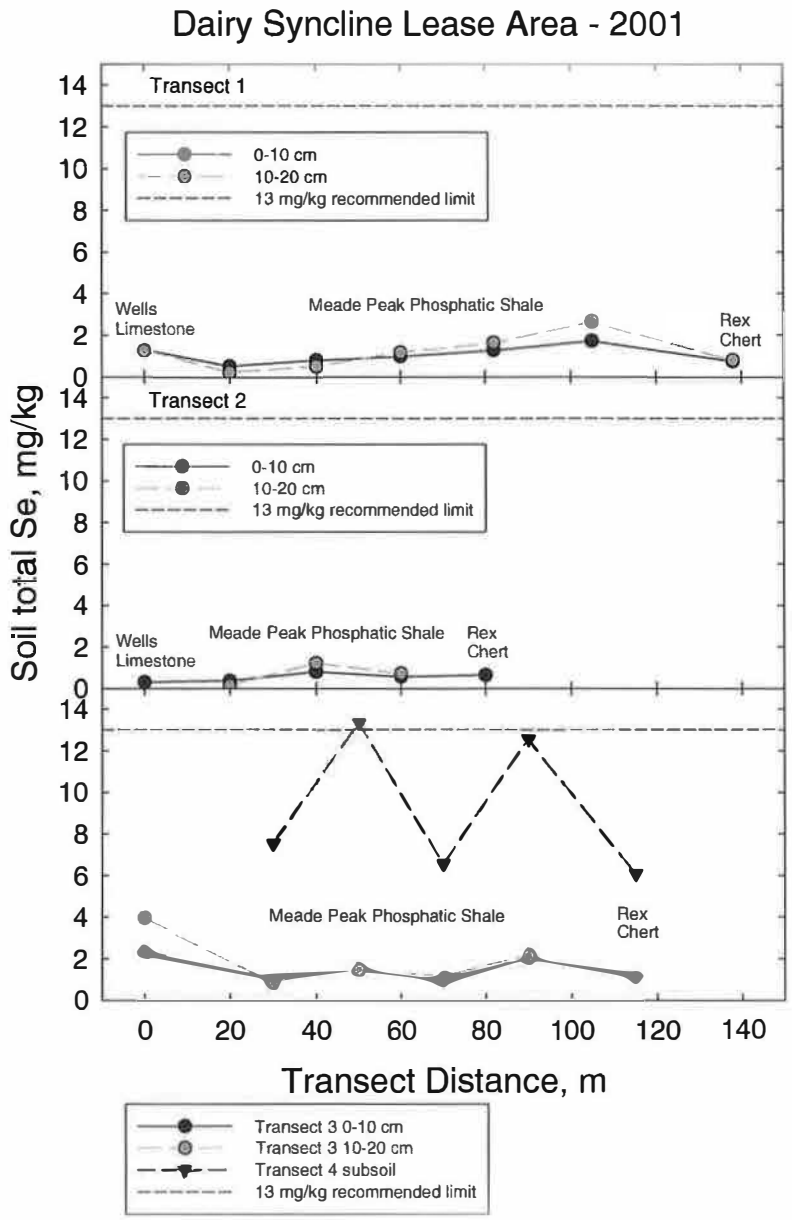


Fig. 11. Total Se in 0-10 cm, 10-20 cm, and subsoil soil samples along transects across sedimentary rock units (Wells limestone, Meade Peak phosphatic shale, and Rex chert) at Dairy Syncline lease area in 2001. Transects 1 and 2 were at undisturbed sites, transect 3 was along the top of an old exploration trench, and transect 4 was along the base of the trench in the subsoil weathered parent material.

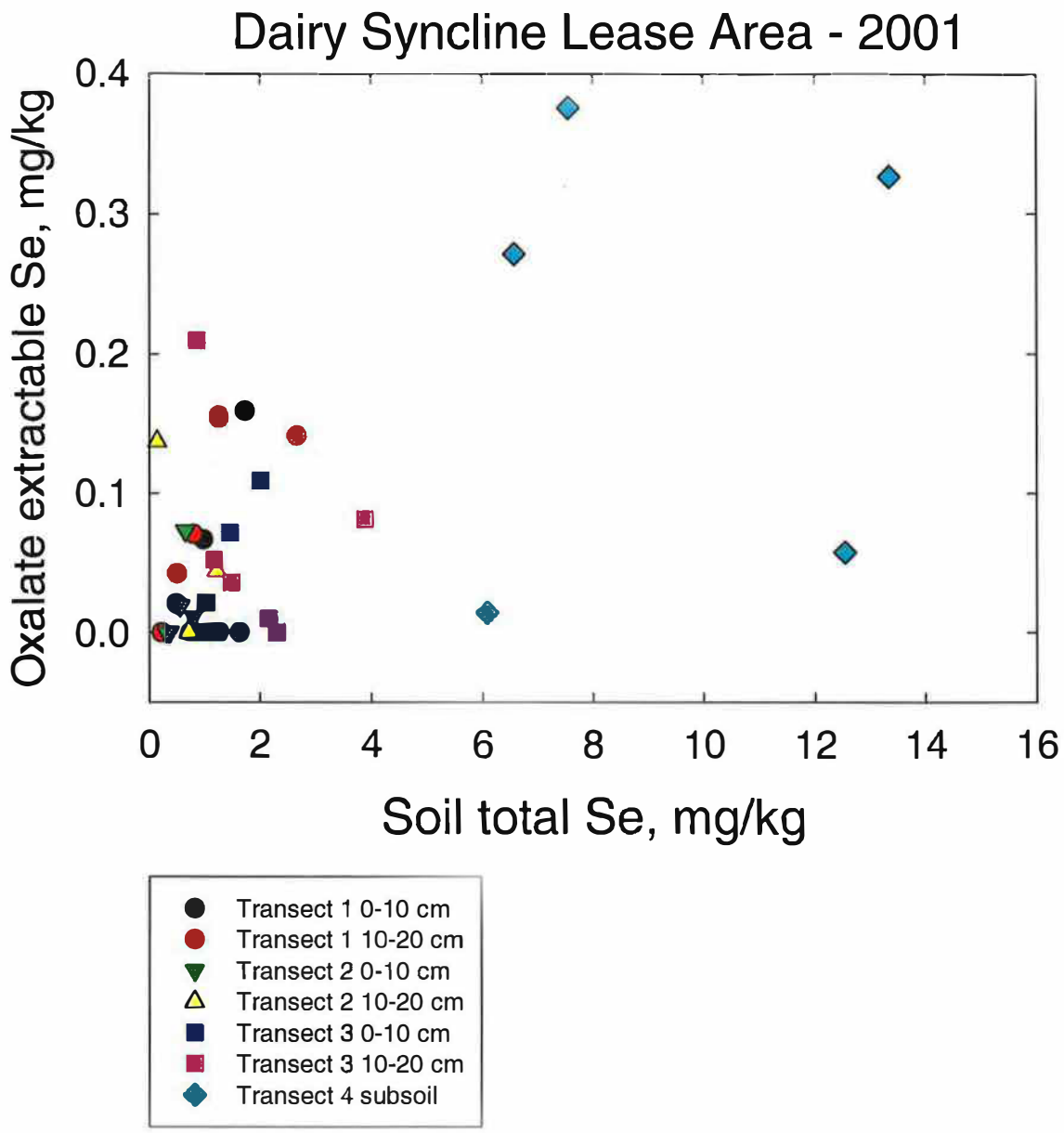


Fig. 12. Relationship between oxalate-extractable and total Se in 0-10 cm, 10-20 cm, and subsoil soil samples collected along transects across sedimentary rock units (Wells limestone, Meade Peak phosphatic shale, and Rex chert) at Dairy Syncline lease area in 2001. Transects 1 and 2 were at undisturbed sites, transect 3 was along the top of an old exploration trench, and transect 4 was along the base of the trench in the weathered parent material.

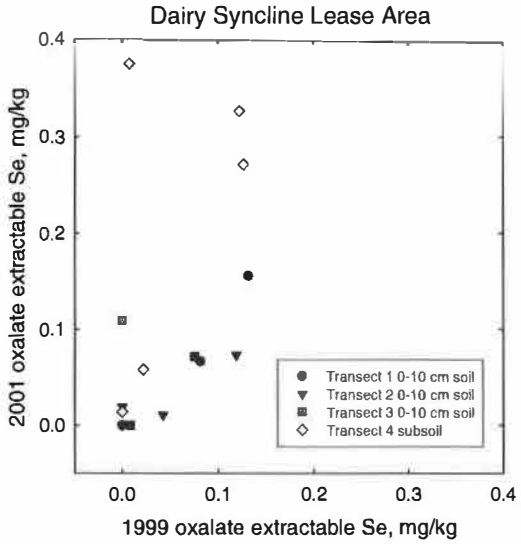


Fig. 13. Relationship between oxalate-extractable Se in soil samples collected in 1999 and oxalate-extractable Se in soil samples collected in 2001 along transects across sedimentary rock units (Wells limestone, Meade Peak phosphatic shale, and Rex chert) at Dairy Syncline lease area. Transects 1 and 2 were at undisturbed sites, transect 3 was along the top of an old exploration trench, and transect 4 was along the base of the trench in the subsoil weathered parent material.

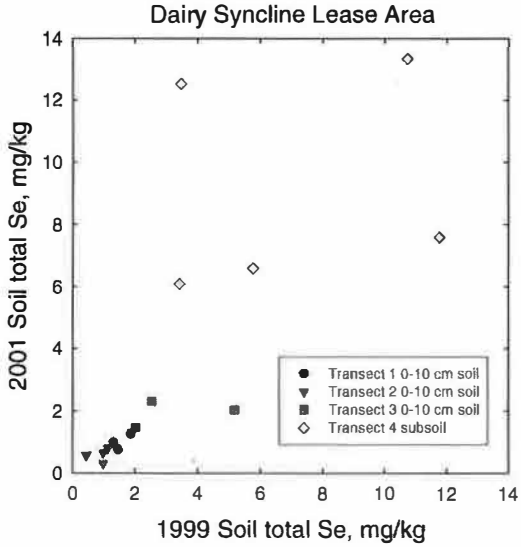


Fig. 14. Relationship between total Se in soil samples collected in 1999 and total Se in soil samples collected in 2001 along transects across sedimentary rock units (Wells limestone, Meade Peak phosphatic shale, and Rex chert) at Dairy Syncline lease area. Transects 1 and 2 were at undisturbed sites, transect 3 was along the top of an old exploration trench, and transect 4 was along the base of the trench in the subsoil weathered parent material.

No relationship was found between plant Se concentrations and oxalate-extractable or total Se in either the 1999 (Figs. 15 and 16) or 2001 (Figs. 17 and 18) soil samples. Given the low levels of both plant and soil Se at the Dairy Syncline lease area, this is not surprising. Because all the plant samples from this area had Se concentrations well below the 5 mg/kg recommended limit for forages, topsoil total Se concentrations were well below the 13 mg/kg recommended limit for soil capping materials, and subsoil total Se concentrations were at or below the 13 mg/kg recommended limit, we foresee no problem in using any of the Dairy Syncline lease area soils as waste rock dump caps for plant community establishment.

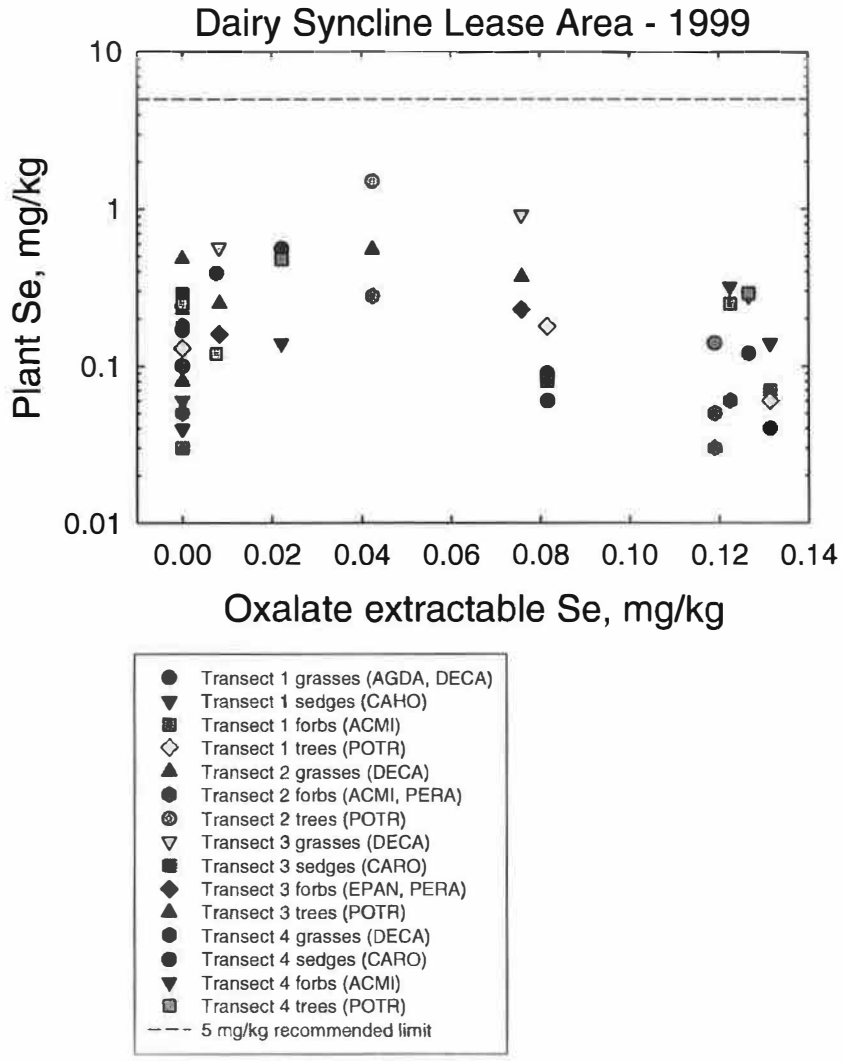


Fig. 15. Relationship between plant Se concentrations and oxalate-extractable soil Se along transects across sedimentary rock units (Wells limestone, Meade Peak phosphatic shale, and Rex chert) at Dairy Syncline lease area in 1999. Transects 1 and 2 were at undisturbed sites, transect 3 was along the top of an old exploration trench, and transect 4 was along the base of the trench in the subsoil weathered parent material.

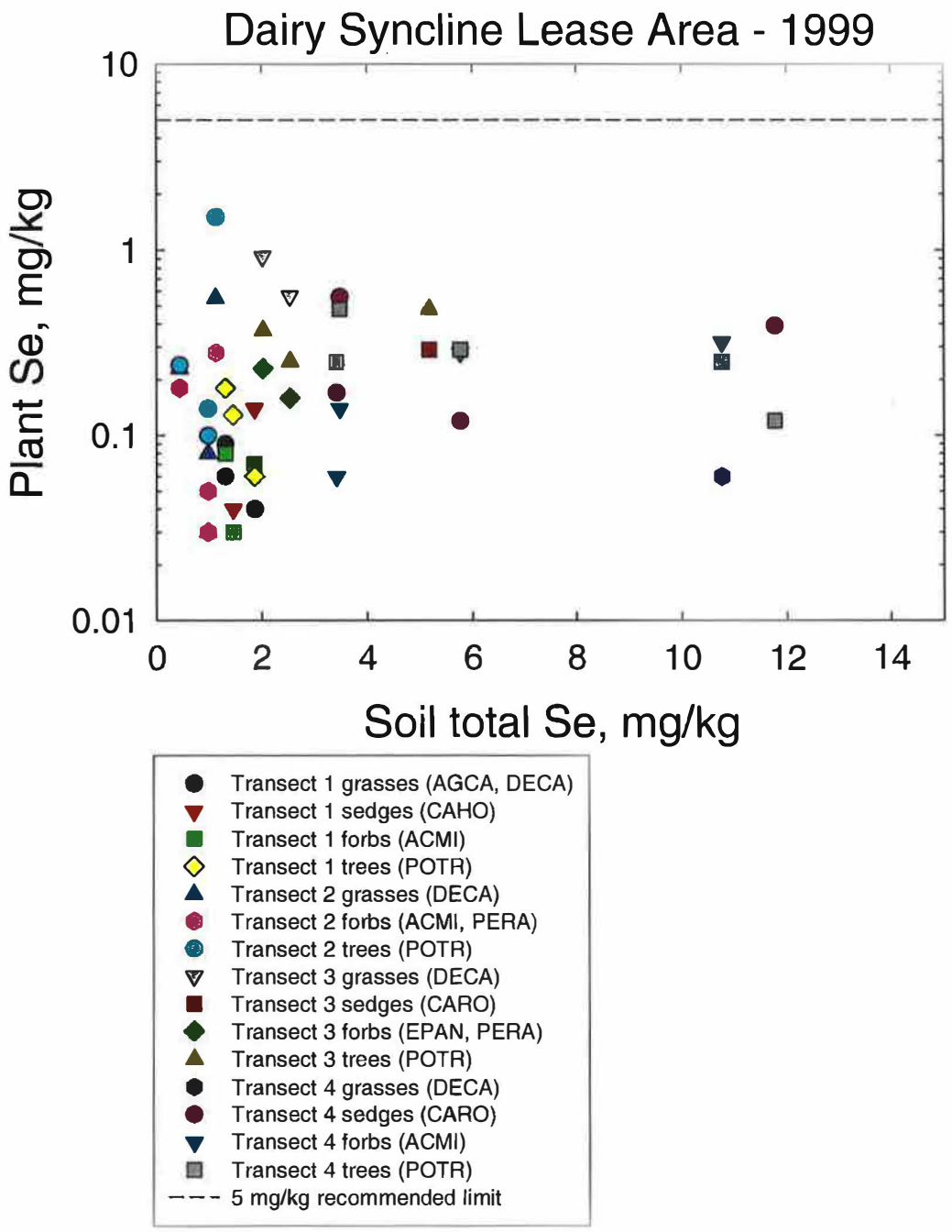


Fig. 16. Relationship between plant Se concentrations and soil total Se along transects across sedimentary rock units (Wells limestone, Meade Peak phosphatic shale, and Rex chert) at Dairy Syncline lease area in 1999. Transects 1 and 2 were at undisturbed sites, transect 3 was along the top of an old exploration trench, and transect 4 was along the base of the trench in the subsoil weathered parent material.

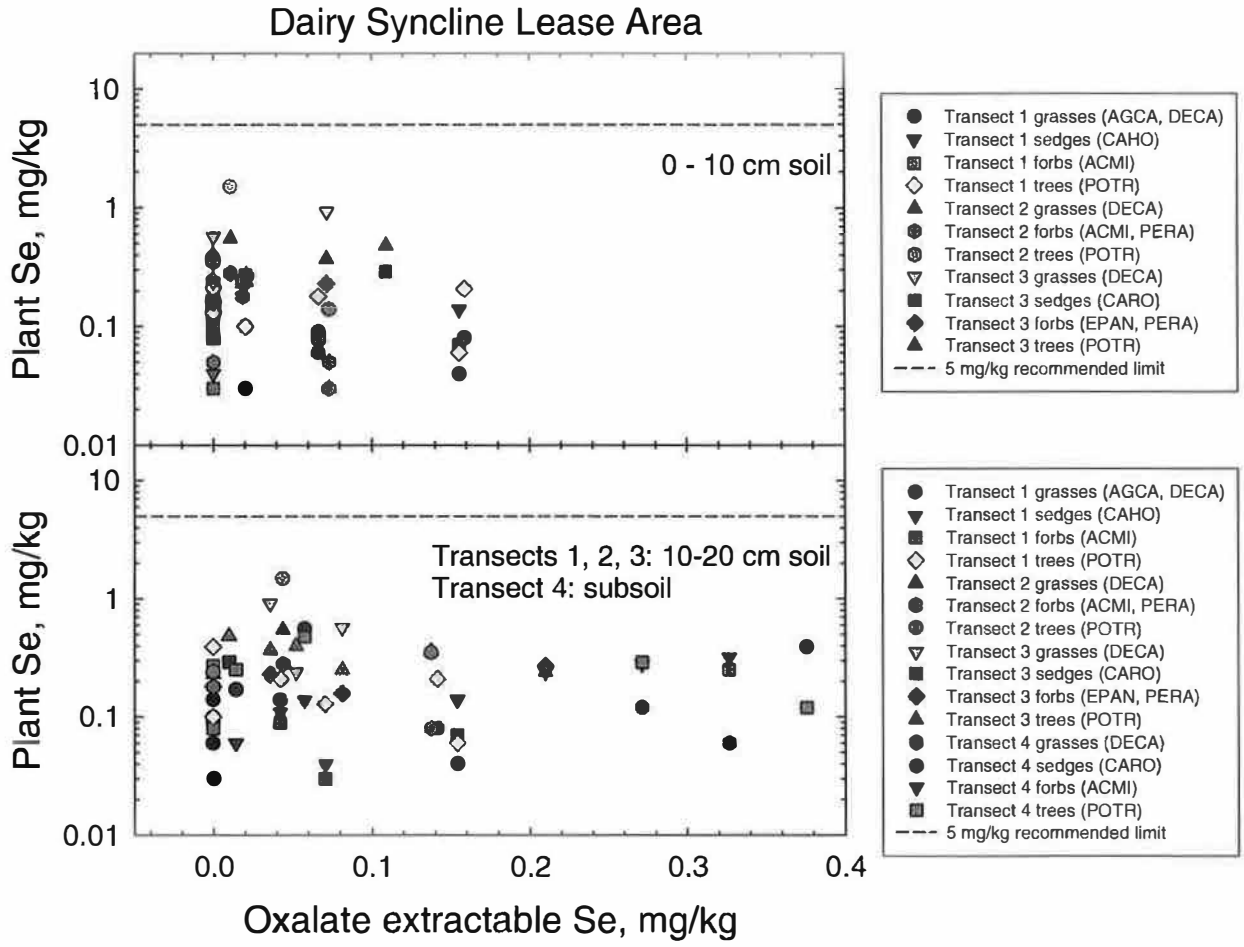


Fig. 17. Relationship between 1999 plant Se concentrations and 2001 oxalate-extractable soil Se along transects across sedimentary rock units (Wells limestone, Meade Peak phosphatic shale, and Rex chert) at Dairy Syncline lease area. Transects 1 and 2 were at undisturbed sites, transect 3 was along the top of an old exploration trench, and transect 4 was along the base of the trench in the subsoil weathered parent material.

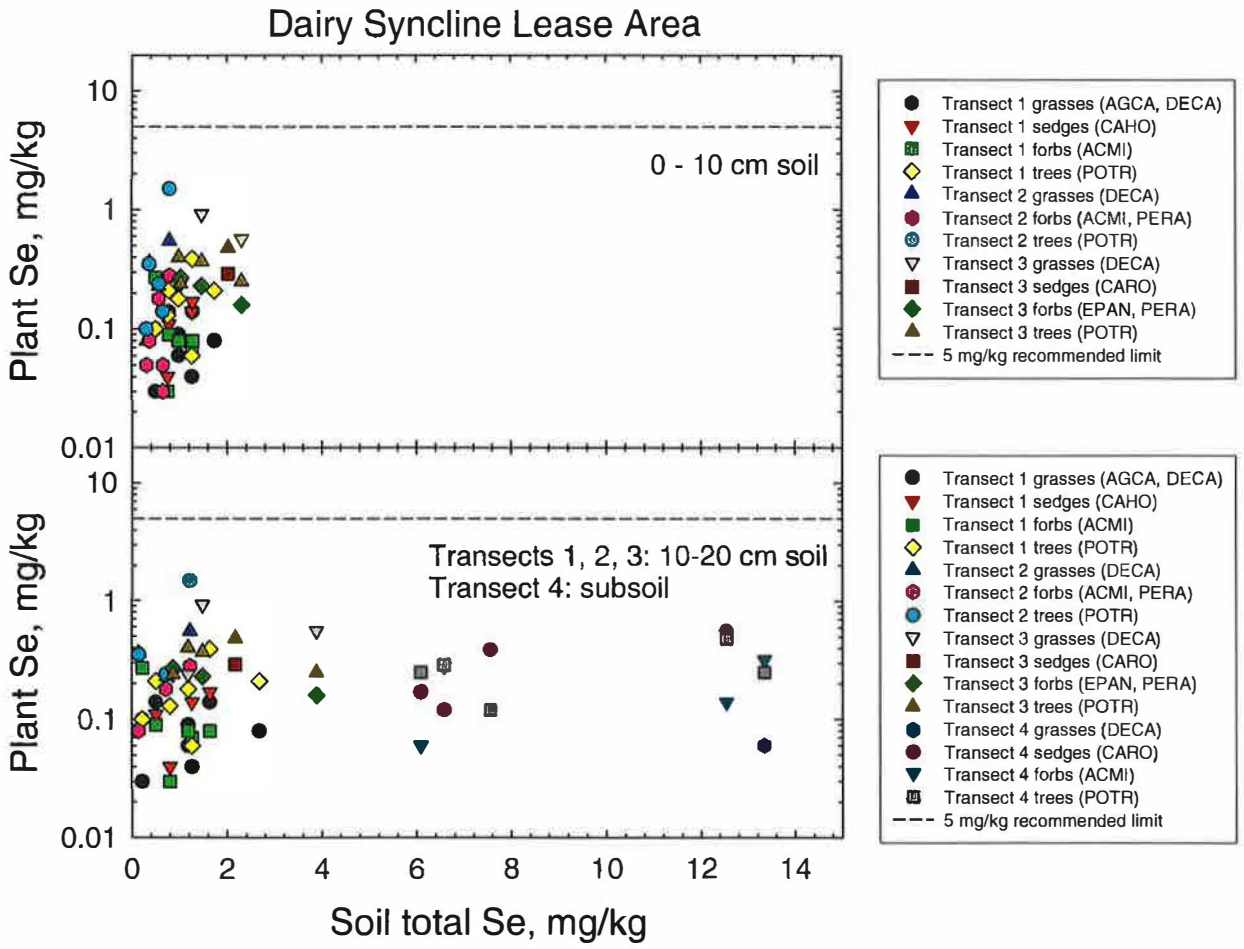

Dairy Syncline Lease Area
Plant Se, mg/kg
0 - 10 cm soil
Transects 1, 2, 3: 10-20 cm soil
Transect 4: subsoil
Soil total Se, mg/kg
Transect 1 grasses (AGCA, DECA)
Transect 1 sedges (CAHO)
Transect 1 forbs (ACMI)
Transect 1 trees (POTR)
Transect 2 grasses (DECA)
Transect 2 forbs (ACMI, PERA)
Transect 2 trees (POTR)
Transect 3 grasses (DECA)
Transect 3 sedges (CARO)
Transect 3 forbs (EPAN, PERA)
Transect 3 trees (POTR)
Transect 4 grasses (DECA)
Transect 4 sedges (CARO)
Transect 4 forbs (ACMI)
Transect 4 trees (POTR)
5 mg/kg recommended limit

Fig. 18. Relationship between 1999 plant Se concentrations and 2001 soil total Se along transects across sedimentary rock units (Wells limestone, Meade Peak phosphatic shale, and Rex chert) at Dairy Syncline lease area. Transects 1 and 2 were at undisturbed sites, transect 3 was along the top of an old exploration trench, and transect 4 was along the base of the trench in the subsoil weathered parent material.

Deer Creek Lease Area:

Two sites were sampled at the Deer Creek lease area. At one site, a transect was established across the Phosphoria Formation and ran along the base of the hill along a side drainage to the main channel. The other location was an old exploration trench at the junction of a small drainage and the main channel. Elevated levels of plant and 0 – 10 cm soil oxalate-extractable and total Se were found overlying the Meade Peak member as compared to the Wells limestone and Rex chert members (Fig. 19). Only two plant species were sampled along this transect – a grass and a shrub (*Elymus cinereus* and *Artemisia tridentata*). All of the plant Se concentrations were below the 5 mg/kg recommended limit, but one of the *Elymus cinereus* samples growing in soil with a total Se level approaching 50 mg/kg had a Se concentration approaching 5 mg/kg (Fig. 19).

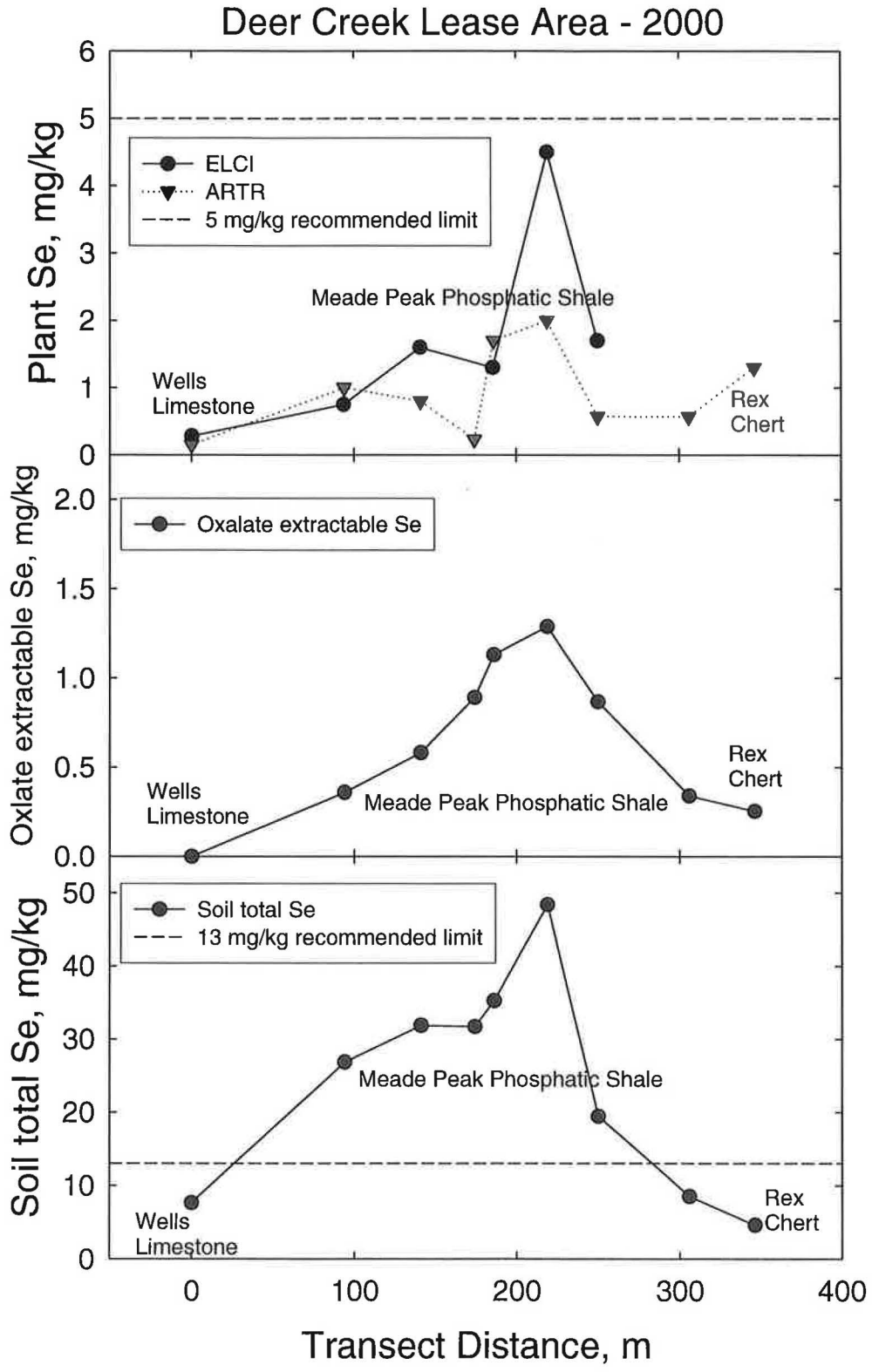


Fig. 19. Plant (top), oxalate-extractable (middle), and soil total (bottom) Se concentrations along a transect across sedimentary rock units (Wells limestone, Meade Peak phosphatic shale, and Rex chert) at Deer Creek lease area in 2000.

Four locations were sampled in an old shallow exploration trench that began on the stream terrace above Deer Creek and ran upslope perpendicular to the main stream channel. Exposed soil in the lower part of the trench was developed in dark-colored phosphatic shale. Two of the sampling locations (DC2-1 and DC2-2) were in the shallow downslope part of the trench at the top of the stream terrace. Sampling locations DC2-3 and DC2-4 were on each side of the upslope part of the trench. The same two plant species (*Elymus cinereus* and *Artemisia tridentata*) sampled along the transect were also sampled at the trench site, but all the plant Se concentrations were below 5 mg/kg including those from each side of the trench where soil total Se concentrations approached 50 mg/kg (Fig. 20).

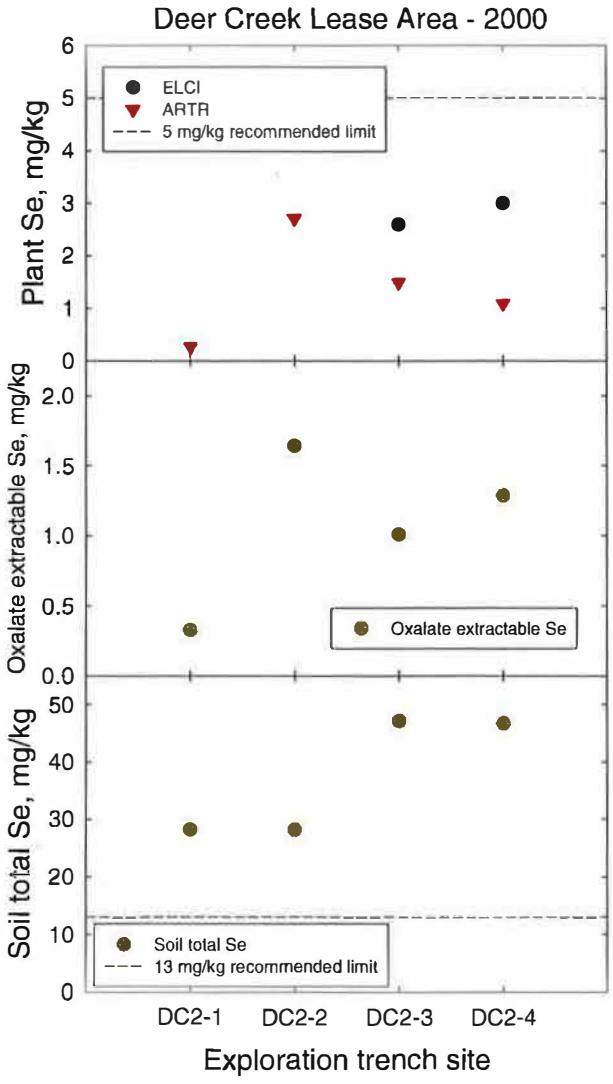


Fig. 20. Plant (top), oxalate-extractable (middle), and soil total (bottom) Se concentrations at an old exploration trench at Deer Creek lease area in 2000. Sites DC2-1 and DC2-2 are in the downslope part of the trench near Deer Creek and sites DC2-3 and DC2-4 are on each side of the upslope part of the trench.

Oxalate-extractable Se levels increased with increasing total Se levels (Fig. 21).

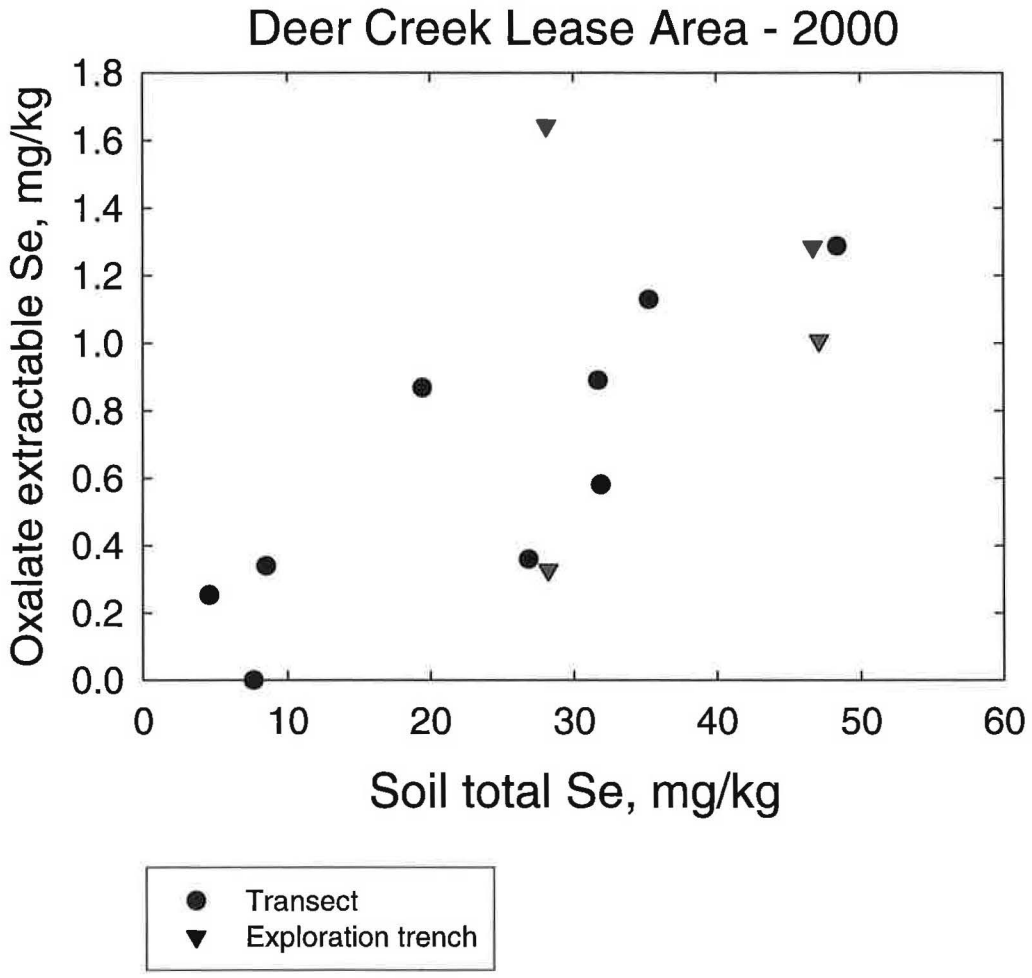


Fig. 21. Relationship between oxalate-extractable and total Se in 0-10 cm soil along a transect across sedimentary rock units (Wells limestone, Meade Peak phosphatic shale, and Rex chert) and at an old exploration trench at Deer Creek lease area in 2000.

No strong relationship between plant Se concentrations and soil oxalate-extractable or total Se was observed at the Deer Creek lease area sampling sites (Fig. 22), although the highest Se concentrations in *Elymus cinereus* were found in the higher total Se level soils.

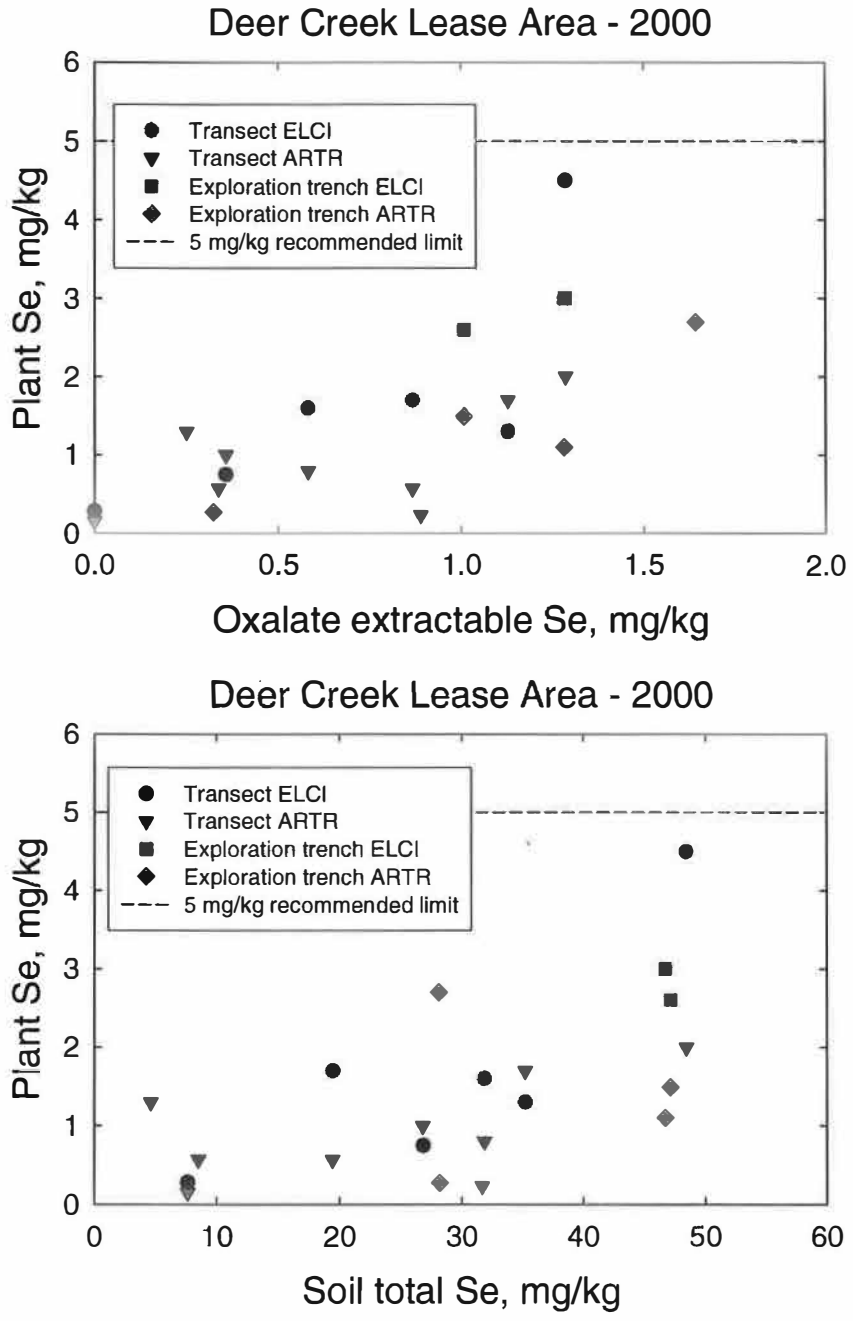


Fig. 22. Relationship between plant Se concentrations and oxalate-extractable (top) and total (bottom) Se in 0-10 cm soil along a transect across sedimentary rock units (Wells limestone, Meade Peak phosphatic shale, and Rex chert) and at an old exploration trench at Deer Creek lease area in 2000.

Deer Creek lease area soils overlying Wells limestone and Rex chert are safe to use as capping materials since plant Se concentrations were well below the 5 mg/kg limit for forages, and soil total Se concentrations were below the 13 mg/kg limit recommended for soil caps. Some caution is warranted with soils overlying the Meade Peak at this location because plant Se concentrations were approaching the 5 mg/kg limit at sites where soil total Se approached 50 mg/kg. We recommend that these higher Se soils be tested in plant uptake experiments before use as capping materials because plant Se uptake will likely increase after the soils are disturbed and stockpiled during the overburden removal process because of increased oxidation similar to the weathering environment at waste rock dumps.

Rasmussen Ridge:

The sampling transect at Rasmussen Ridge was established along the top of a premining bulldozer cut across the Phosphoria Formation. Plant samples were collected from the undisturbed area above the identified sedimentary rock units which included the above the upper ore, upper ore, upper middle waste, lower middle waste, lower ore, and below the lower ore units. All of the plant Se concentrations were well below the 5 mg/kg limit (Fig. 23 top).

Soil cores were collected from the exposed soil profiles at the upper ore, upper middle waste, lower middle waste, and lower ore units, but elevated levels of oxalate-extractable Se were found only at the 150-cm depth of the soil profile overlying the lower ore unit (Fig. 23 bottom) and elevated levels of total Se were only found at about the 150-cm depth of the soil profiles over the upper ore, upper middle waste, and lower ore units (Fig. 24 bottom). Only the 150-cm deep soil core in the lower ore unit exceeded the 13 mg/kg limit for soil caps. Since these soils were deep and well developed, and had few soil roots at the 150-cm depth where most of the total Se was found, Se concentrations in the plants remained low (Fig. 23 top).

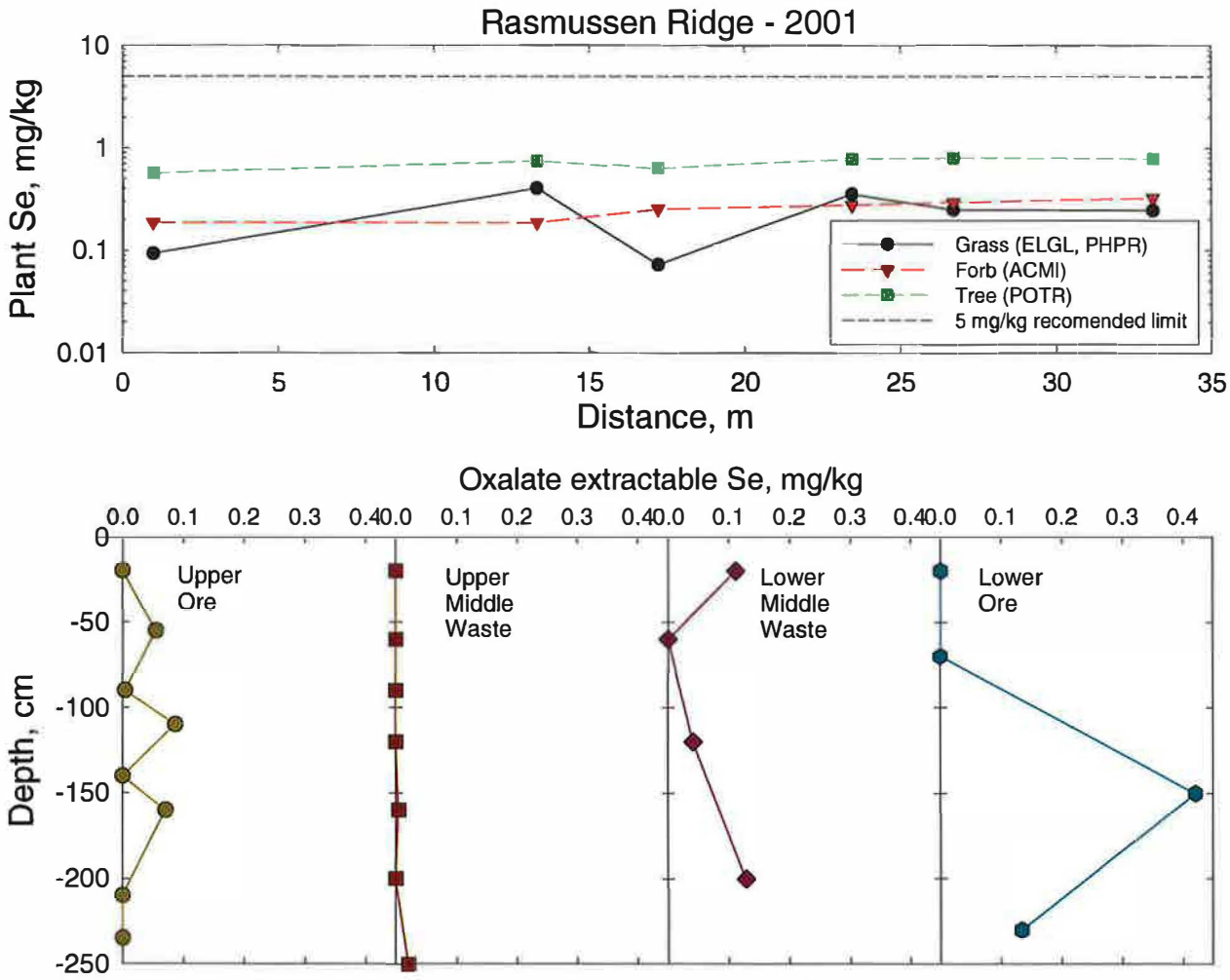


Fig. 23. Se concentrations in various plant lifeforms (top) along a transect across Meade Peak phosphatic shale members (upper ore, upper middle waste, lower middle waste, and lower ore) at Rasmussen Ridge in 2001 and corresponding soil and sedimentary rock unit oxalate-extractable Se concentrations by depth at the same locations (bottom).

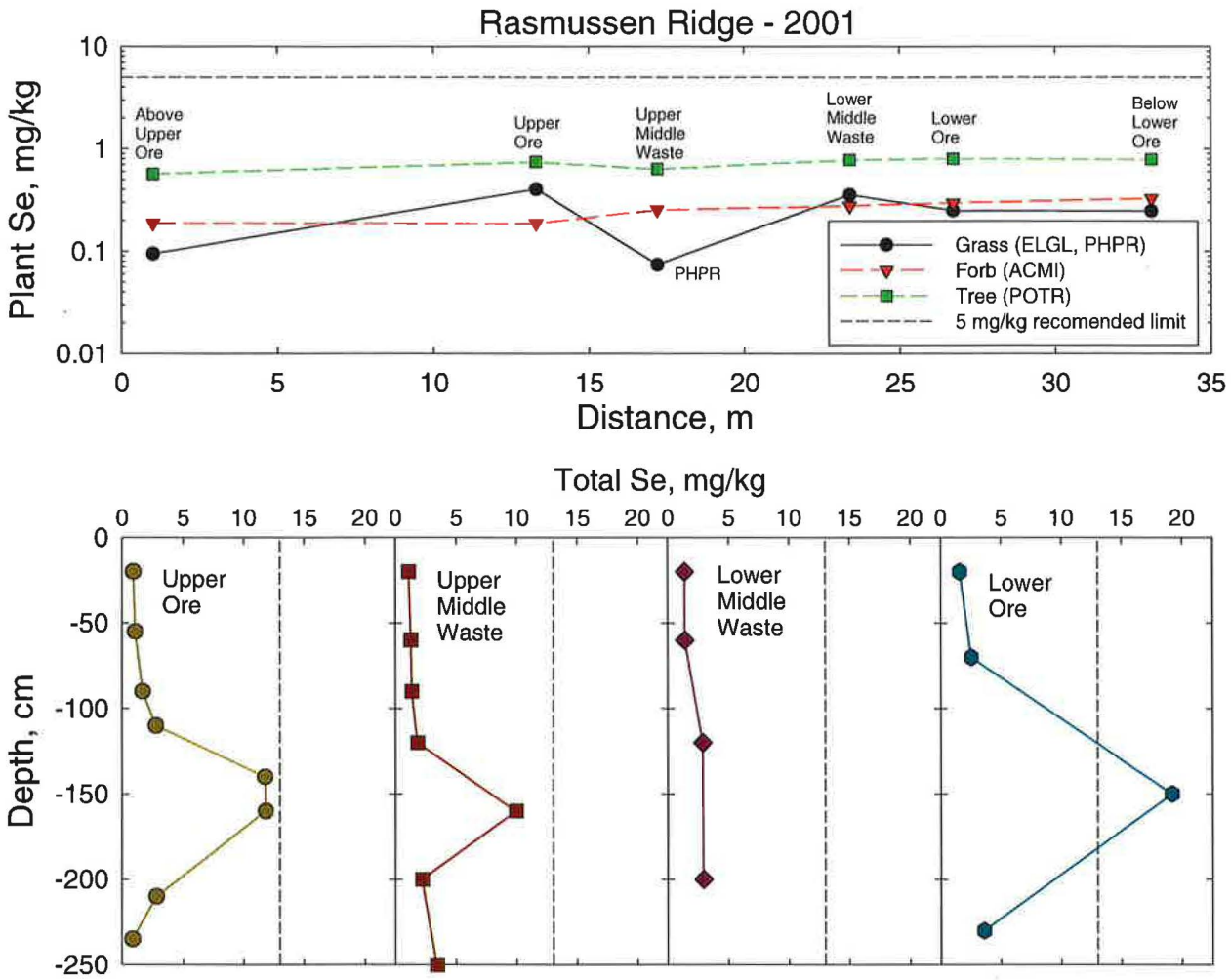


Fig. 24. Se concentrations in various plant lifeforms (top) along a transect across Meade Peak phosphatic shale members (upper ore, upper middle waste, lower middle waste, and lower ore) at Rasmussen Ridge in 2001 and corresponding soil and sedimentary rock unit total Se concentrations by depth at the same locations (bottom). The vertical dashed lines in the total Se plots represent the 13 mg/kg recommended limit for soil capping material.

No relationship between oxalate-extractable and total Se was found (Fig. 25).

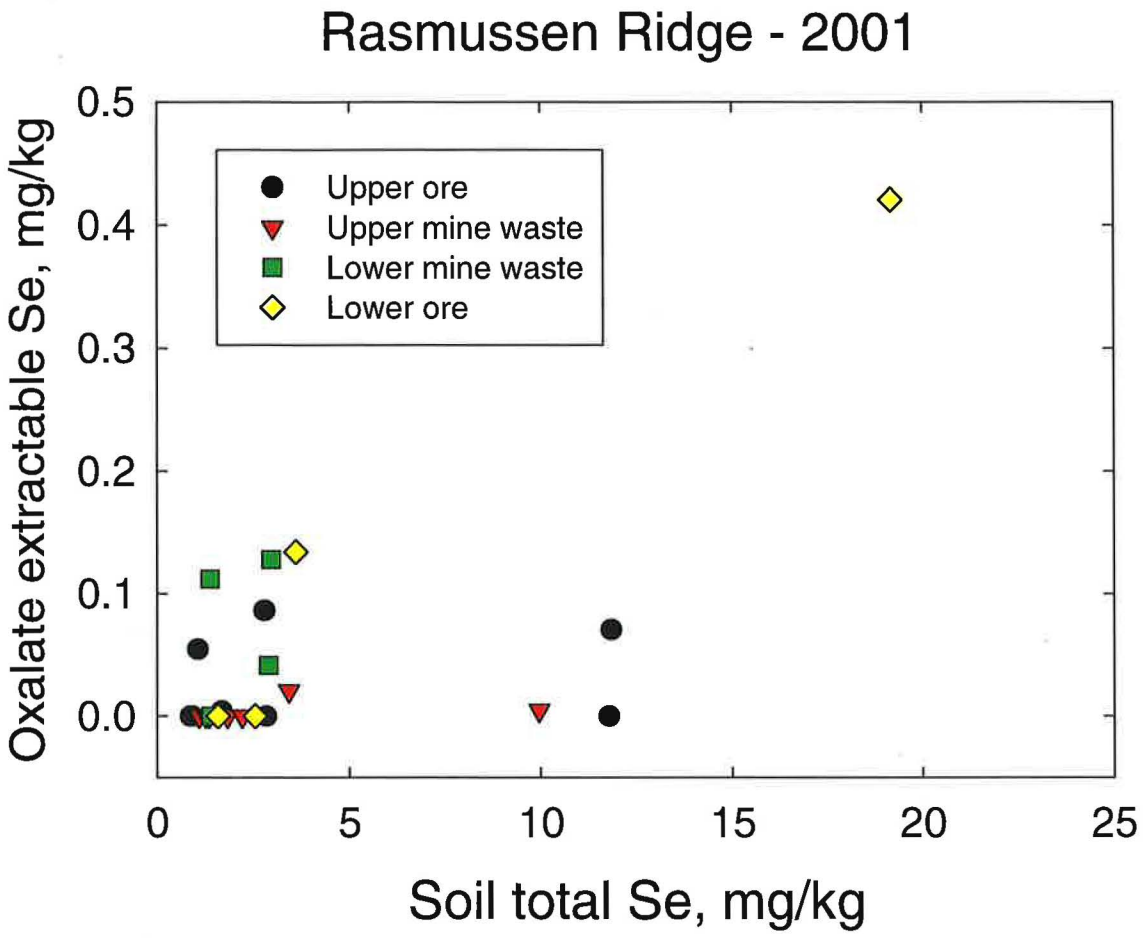


Fig. 25. Relationship between soil oxalate-extractable and total Se in soil samples collected at various depths along a transect across Meade Peak phosphatic shale members (upper ore, upper middle waste, lower middle waste, and lower ore) at Rasmussen Ridge in 2001.

No relationship between plant Se concentrations and oxalate-extractable or soil total Se was found at Rasmussen Ridge (Fig. 26), which is not surprising given the low levels of soil Se found at this site. Soils at this site would be suitable for use as capping materials since higher levels of Se are only found deep in the soil profile (about 150 cm). Thus, the upper meter of soil could be used as a waste rock dump cap with little risk of increased plant uptake of Se.

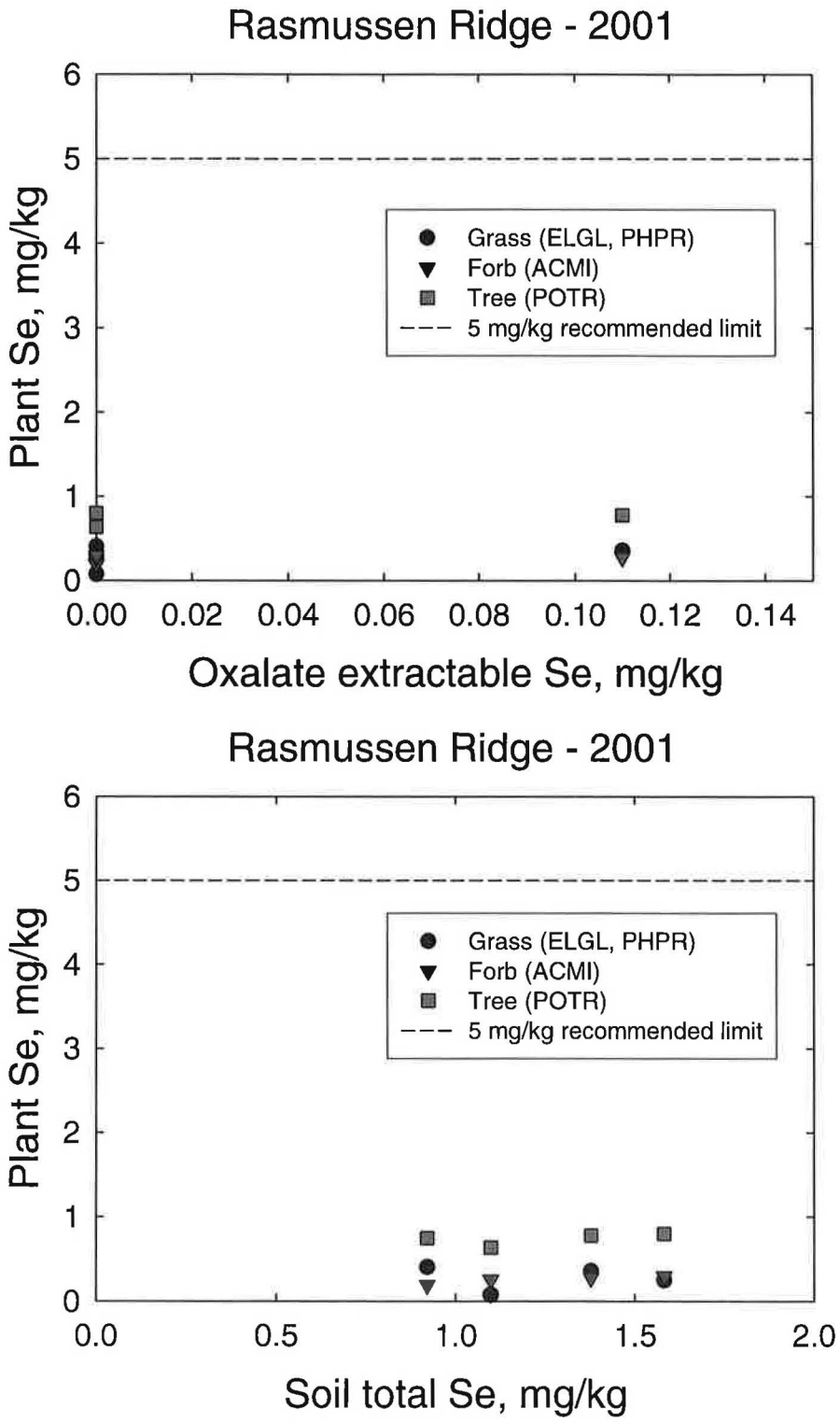


Fig. 26. Relationship between plant Se concentrations and 20-cm depth soil oxalate-extractable (top) and total (bottom) Se along a transect across Meade Peak phosphatic shale members (upper ore, upper middle waste, lower middle waste, and lower ore) at Rasmussen Ridge in 2001.

Maybe Canyon:

Although the Phosphoria Formation at Maybe Canyon has been mined extensively, some sections of the formation between mining trenches remain undisturbed. There is an old collapsed adit along the road adjacent to Maybe Canyon Creek. Upslope from the adit is what appears to be an old exploration area. A transect was established in 2001 across the Phosphoria Formation in the partially disturbed exploration area upslope from the collapsed adit. Elevated concentrations of plant and soil oxalate-extractable and total Se were found overlying the Meade Peak member as compared to the Wells limestone and Rex chert members (Fig. 27). Mean ± standard error plant Se concentrations are shown in Fig. 27. Differences among the various plant species are shown in Fig. 28. Several plant species had Se concentrations above 5 mg/kg at locations in the Meade Peak member where soil total Se exceeded 50 mg/kg (Fig. 28).

Because the site sampled in 2001 was partially disturbed and the disturbance might account in part for the elevated levels of Se because of increased exposure to soil weathering processes, an additional transect was sampled in 2002 in an undisturbed area upslope from the 2001 transect. Selenium concentrations above 5 mg/kg were found in two aspen samples overlying the Meade Peak and several other plant species had Se concentrations approaching 5 mg/kg at the locations where soil total Se exceeded 50 mg/kg (Fig. 29).

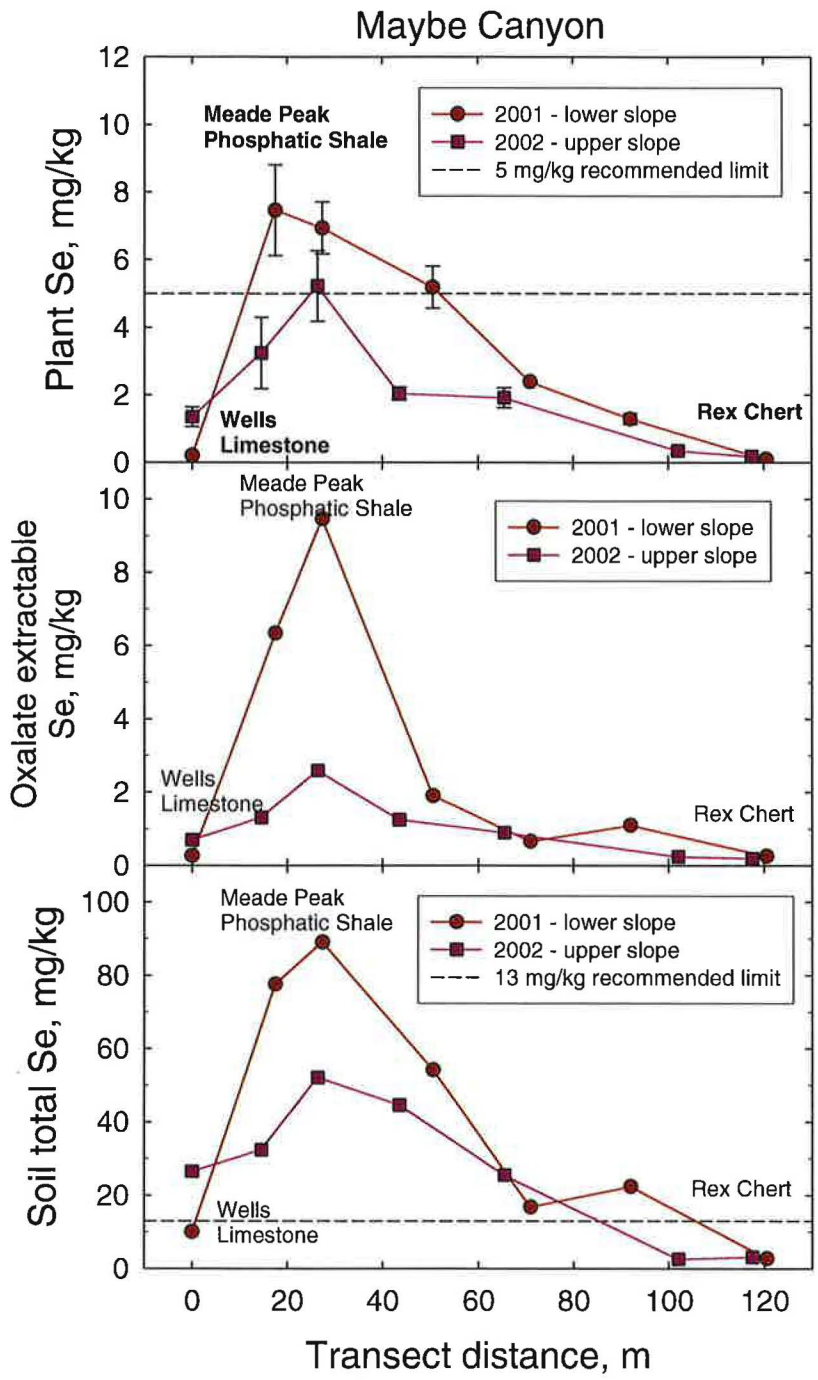


Fig. 27. Mean plant (top) and soil oxalate-extractable (middle) and total (bottom) Se concentrations along transects across sedimentary rock units (Wells limestone, Meade Peak phosphatic shale, and Rex chert) at Maybe Canyon in 2001 and 2002. The 2001 transect was across an old exploration trench upslope from the collapsed Maybe Canyon adit. The 2002 transect was across an undisturbed area upslope from the exploration trench and the 2001 transect. Symbols on the plant Se graph represent mean ± standard error Se concentrations for all plant species.

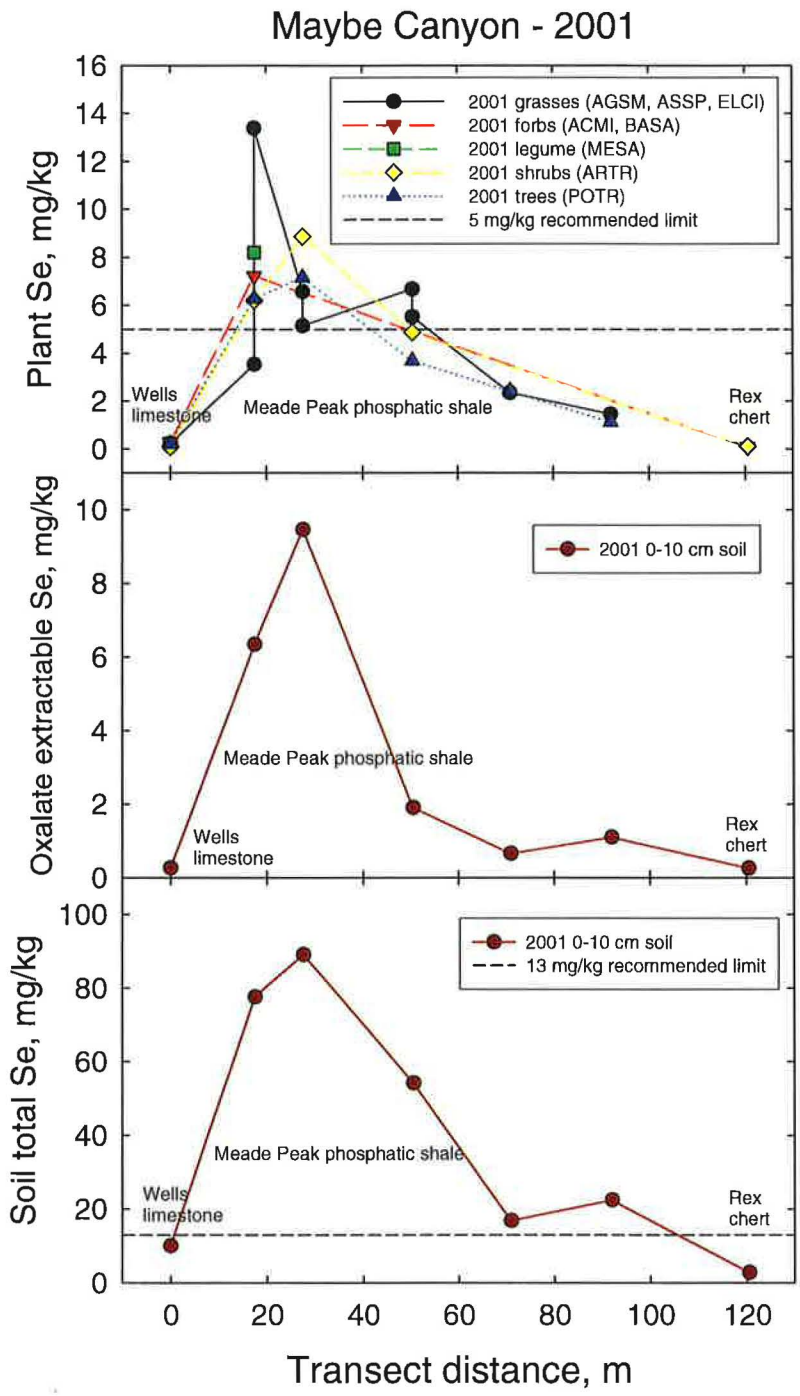


Fig. 28. Se concentrations in various plant lifeforms (top) and corresponding soil oxalate-extractable (middle) and total (bottom) Se concentrations along transects across sedimentary rock units (Wells limestone, Meade Peak phosphatic shale, and Rex chert) at Maybe Canyon in 2001. The 2001 transect was across an old exploration trench upslope from the collapsed Maybe Canyon adit.

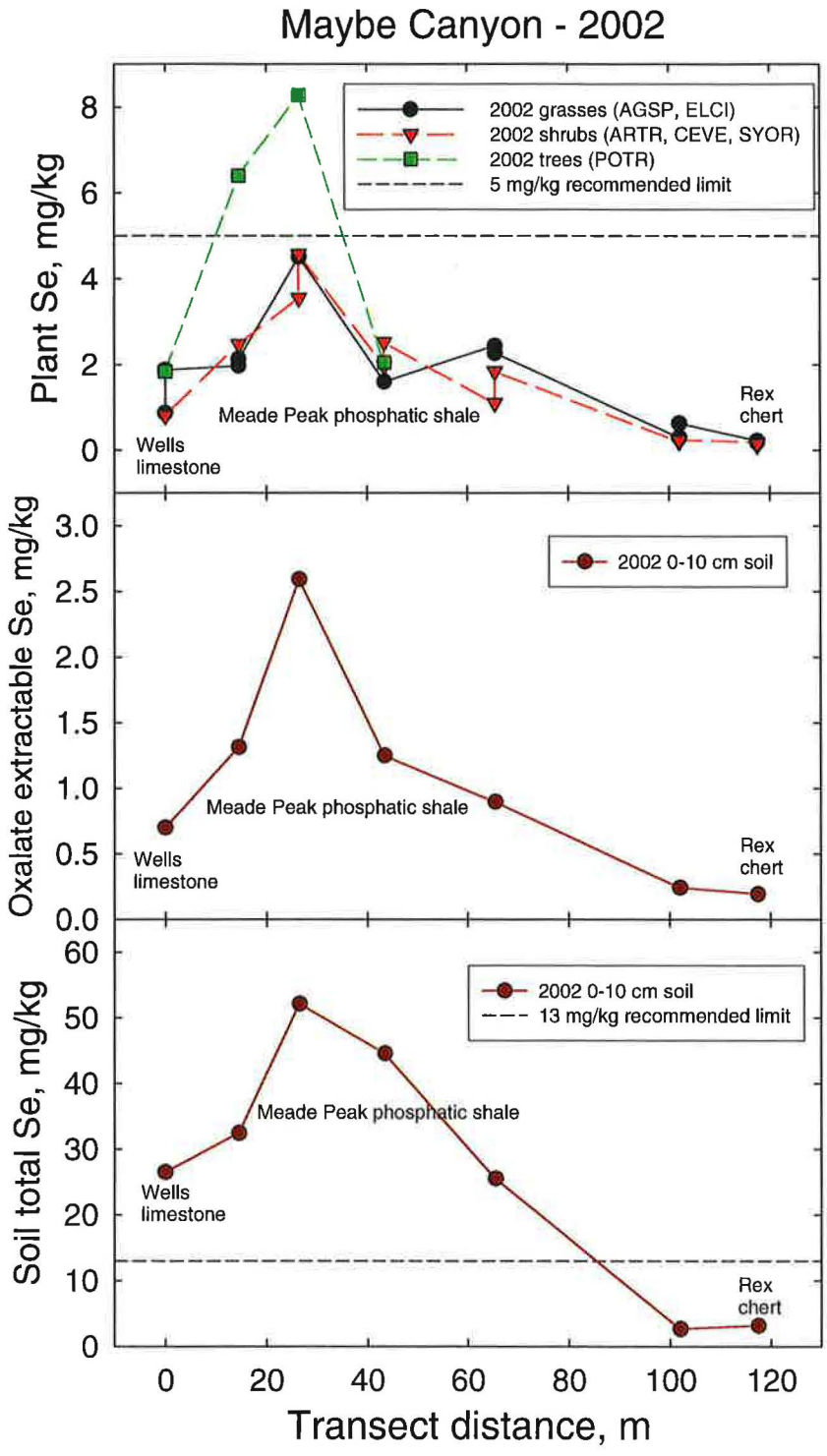


Fig. 29. Se concentrations in various plant lifeforms (top) and corresponding soil oxalate-extractable (middle) and total (bottom) Se concentrations along transects across sedimentary rock units (Wells limestone, Meade Peak phosphatic shale, and Rex chert) at Maybe Canyon in 2002. The 2002 transect was across an undisturbed area upslope from the exploration trench and the 2001 transect.

An exponential increase in oxalate-extractable Se with increasing total Se was found in the soil samples collected at Maybe Canyon (Fig. 30). This increase was well-described with an exponential model.

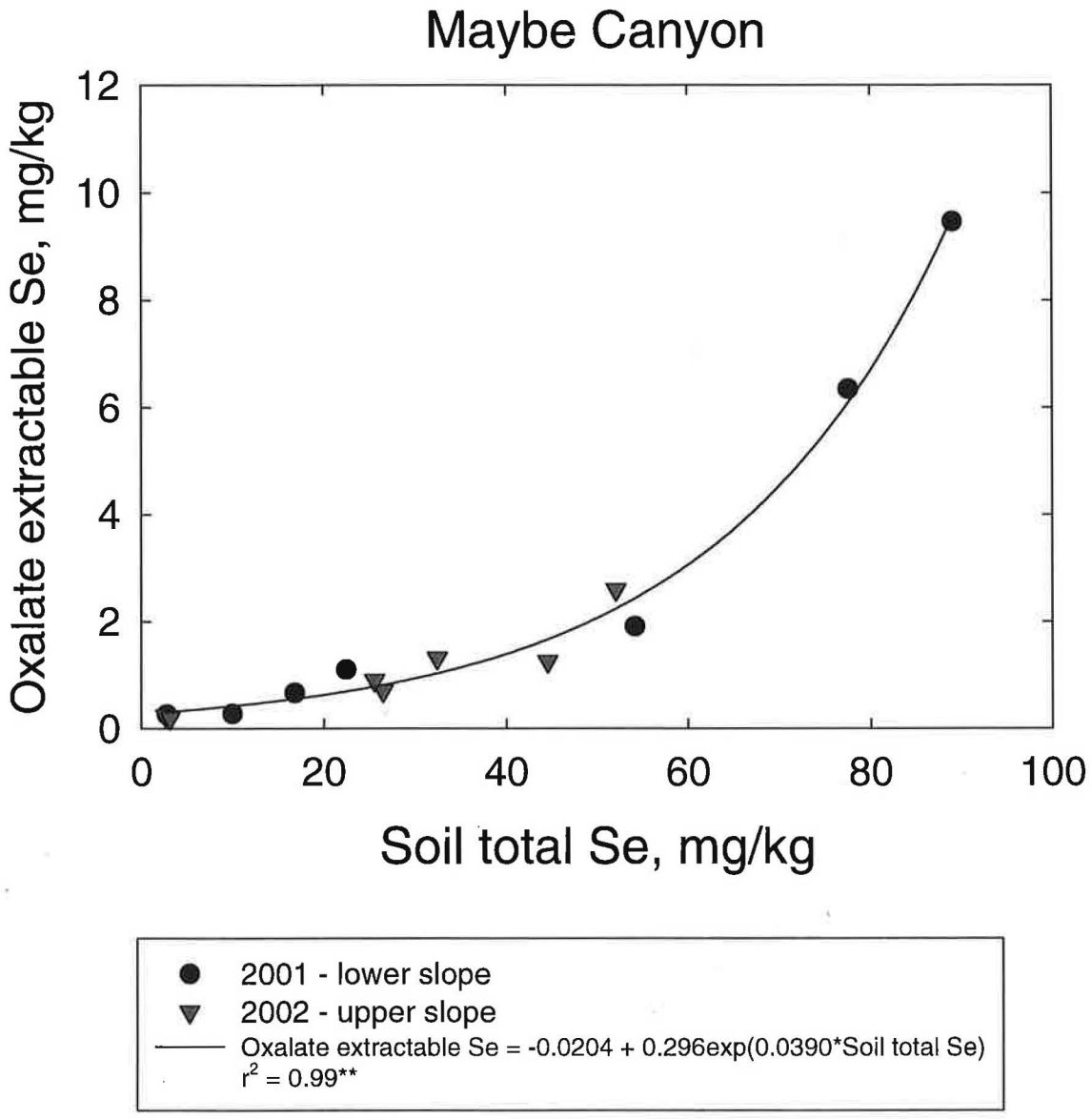


Fig. 30. Relationship between oxalate-extractable and total Se in 0-10 cm soil samples along transects across sedimentary rock units (Wells limestone, Meade Peak phosphatic shale, and Rex chert) at Maybe Canyon in 2001 and 2002. The 2001 transect was across an old exploration trench upslope from the collapsed Maybe Canyon adit. The 2002 transect was across an undisturbed area upslope from the exploration trench and the 2001 transect.

Overall, plant lifeforms had similar Se concentrations (Fig. 31) because location along the transect and the Phosphoria Formation member were the primary influences on plant and soil Se concentrations (Figs. 28 and 29). The one legume (alfalfa) sample

had a Se concentration near the upper range of values for most of the other sampled lifeforms in this area, which is not surprising since alfalfa and other legumes were found to accumulate more Se than grasses and other lifeforms on waste rock dumps (Mackowiak et al. 2004). Aspen was the only plant species sampled along the 2002 transect that had Se concentrations above the 5 mg/kg limit (Fig. 29). Because this location was undisturbed and the soil depth to the Meade Peak was unknown, the large deep rooting volume of aspen may have been able to encounter available Se at deeper depths than the other sampled species.

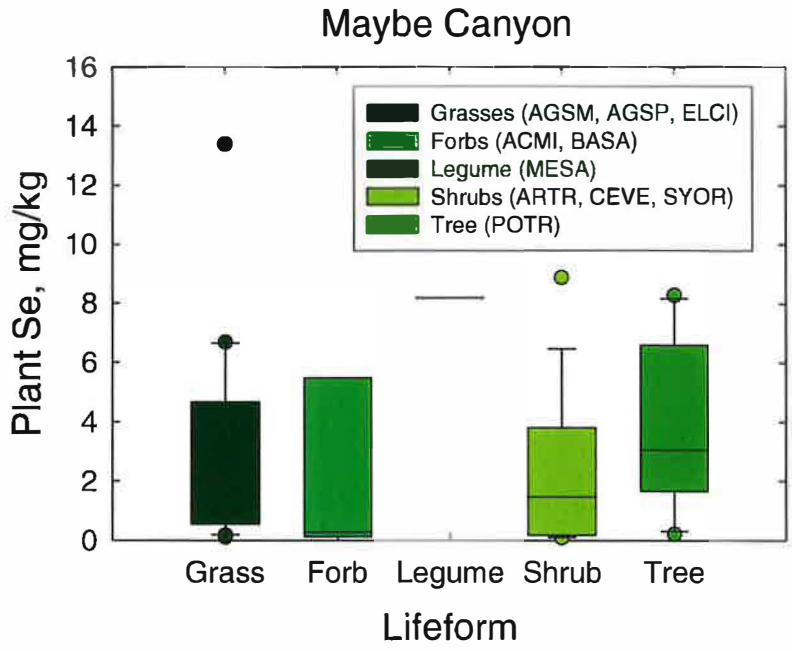


Fig. 31. Se concentrations in various plant lifeforms along transects across sedimentary rock units (Wells limestone, Meade Peak phosphatic shale, and Rex chert) at Maybe Canyon in 2001 and 2002. The 2001 transect was across an old exploration trench upslope from the collapsed Maybe Canyon adit. The 2002 transect was across an undisturbed area upslope from the exploration trench and the 2001 transect. The 25th and 75th percentiles are shown as a box around the median (50th percentile, the 10th and 90th percentiles are shown as error bars and the 5th and 95th percentiles and outliers are shown as points.

When plant Se concentrations for all species were plotted against 0 – 10 cm soil oxalate-extractable or total Se concentrations for both transects, a strong linear relationship was observed using a log scale (Fig. 32). Regressing mean Se concentrations for all plant species against soil oxalate-extractable Se for both transects produced a highly significant exponential relationship (Fig. 33 top: Plant Se = 7.761(1-exp(-0.366 oxalate-extractable Se, r^2 = 0.97**). Regressing mean Se concentrations for all plant species against soil total Se levels for both transects produced a highly significant linear regression (Fig. 33 bottom: Plant Se = -0.19 + 0.088 soil total Se, r^2= 0.91**). The slope of the regression line indicates that for every 1 mg/kg of soil total Se,

a concentration of about 1/10 that can be expected in plants growing over the Meade Peak member in this area. Thus, to keep plant Se concentrations below the 5 mg/kg limit recommended for forages, oxalate-extractable Se levels in undisturbed soils overlying the Meade Peak member of the Phosphoria Formation should not exceed 1.5 mg/kg and soil total Se levels should not exceed 50 mg/kg (vertical dashed lines in Fig. 33).

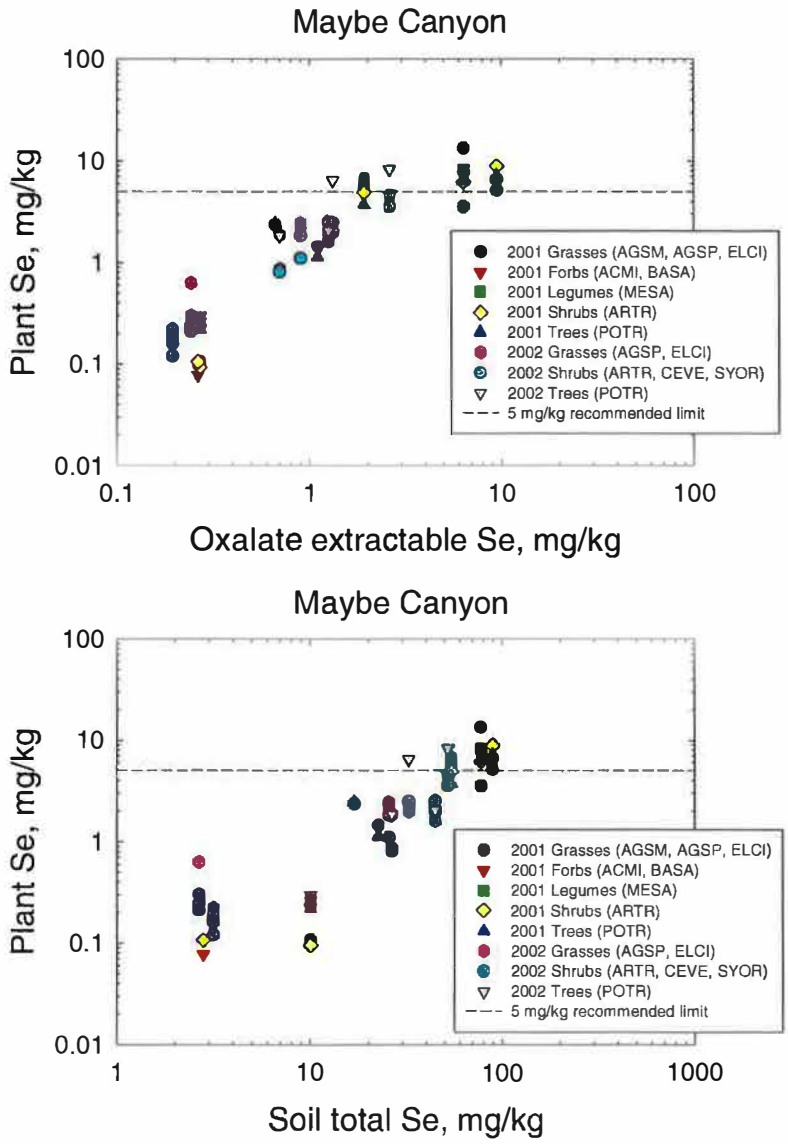


Fig. 32. Relationship between plant Se concentrations and 0-10 cm soil oxalate-extractable (top) and total (bottom) Se along transects across sedimentary rock units (Wells limestone, Meade Peak phosphatic shale, and Rex chert) at Maybe Canyon in 2001 and 2002. The 2001 transect was across an old exploration trench upslope from the collapsed Maybe Canyon adit. The 2002 transect was across an undisturbed area upslope from the exploration trench and the 2001 transect.

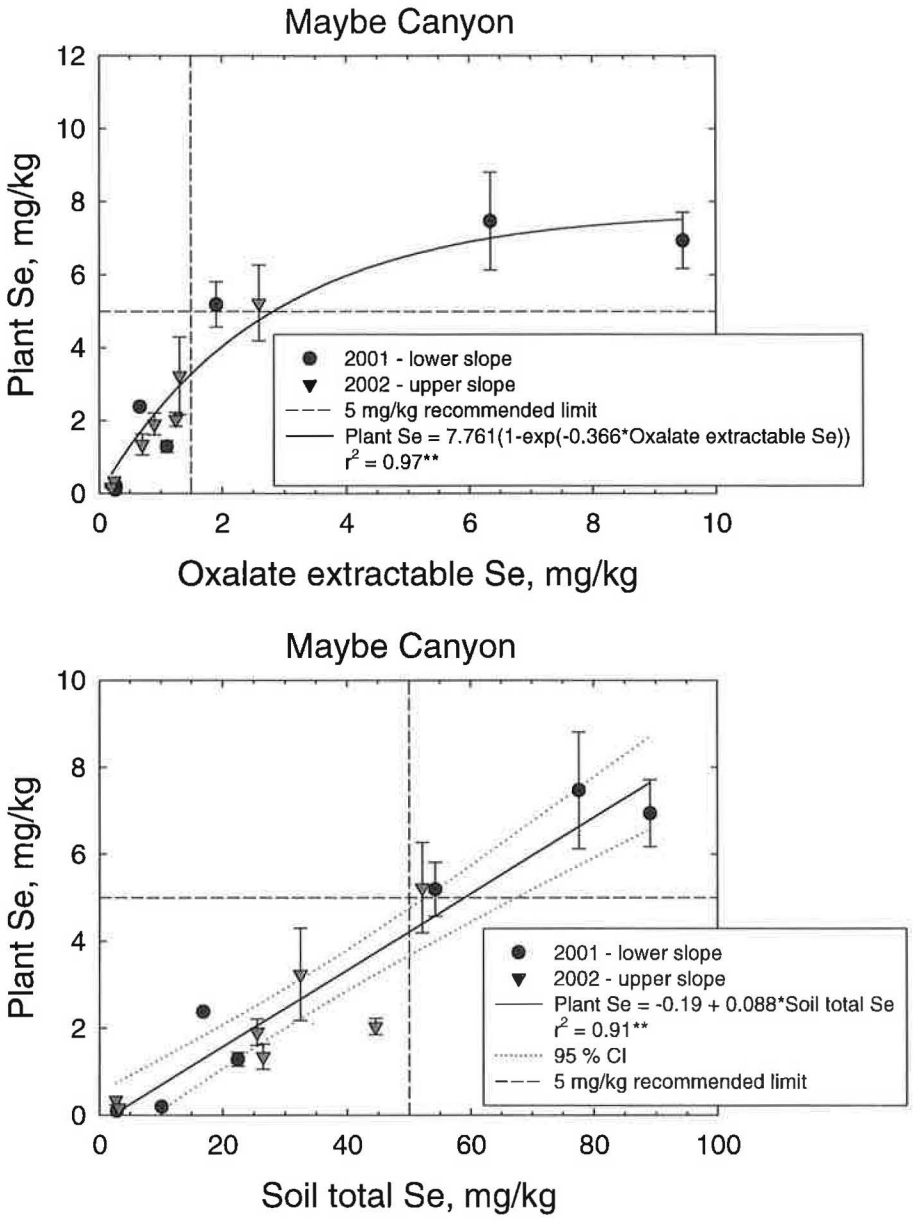


Fig. 33. Relationship between plant Se concentrations and 0-10 cm soil oxalate-extractable (top) and total (bottom) Se along transects across sedimentary rock units (Wells limestone, Meade Peak phosphatic shale, and Rex chert) at Maybe Canyon in 2001 and 2002. Symbols at each soil oxalate-extractable and total Se concentration represent mean ± standard error plant Se concentrations for all species and lifeforms. The best-fit relationship between mean plant Se and oxalate-extractable Se was an exponential model and the best-fit relationship between mean plant Se and soil total Se was a linear regression (solid line with 95% confidence intervals as dotted lines). The 2001 transect was across an old exploration trench upslope from the collapsed Maybe Canyon adit. The 2002 transect was across an undisturbed area upslope from the exploration trench and the 2001 transect.

This result is highly significant because it now sets a recommended upper limit for total Se in undisturbed soils overlying the Meade Peak member of the Phosphoria Formation to be used as a cap in waste rock dump revegetation. Because disturbances only serve to make Se more available for plant uptake because of increased oxidation, undisturbed soils over the Meade Peak with total Se levels in excess of 50 mg/kg should never be used as capping materials because plants growing in these soils already exceed the 5 mg/kg limit for forages.

Disturbed soils with total Se levels less than 13 mg/kg have already been shown to be safe for use as soil caps (Mackowiak and Amacher 2003), but disturbed soils containing between 13 and 50 mg/kg total Se have not been tested for use as capping materials by measuring plant uptake of Se. We recommend that any soil containing between 13 and 50 mg/kg total Se be tested for plant uptake of Se in a glasshouse experiment if it is to be used as a soil cap. A protocol for this testing has been developed (Mackowiak and Amacher 2004).

All reference sites:

Pooling all the plant and soil total Se data for all the unmined reference sites together shows an exponential relationship between plant Se concentrations and soil oxalate-extractable Se (Fig. 34) or total Se (Fig. 35) when the data are plotted on a linear scale. The nature of the exponential relationship between plant Se and oxalate-extractable Se differs from that between plant Se and soil total Se. The exponential relationship between plant Se and oxalate-extractable Se tends to rise to a plateau (no further increase in plant Se with increasing oxalate-extractable Se), whereas plant Se and total Se keep increasing exponentially.

When plotted on a log-log scale, a clear biphasic relationship between plant Se and soil oxalate-extractable or total Se is observed. This biphasic relationship can be described with a two-segment linear regression model (Figs. 36 and 37). Below a threshold level of about 0.2 mg/kg oxalate-extractable Se or 10-15 mg/kg soil total Se, there is no clear relationship between plant and soil total Se, perhaps because extractable and plant available Se levels in such soils are so low. As oxalate-extractable and total Se levels in the soil increase, perhaps because of closer proximity to the elevated levels of Se in Meade Peak phosphatic shale, more Se would be expected to be available for plant uptake and thus a linear relationship between plant and soil oxalate-extractable or total Se is found above a threshold value of 0.2 mg/kg oxalate-extractable Se or 10-15 mg/kg soil total Se (Figs. 36 and 37). The soil total Se threshold value overlaps with the 13 mg/kg recommended limit for total Se in disturbed soils used as capping materials.

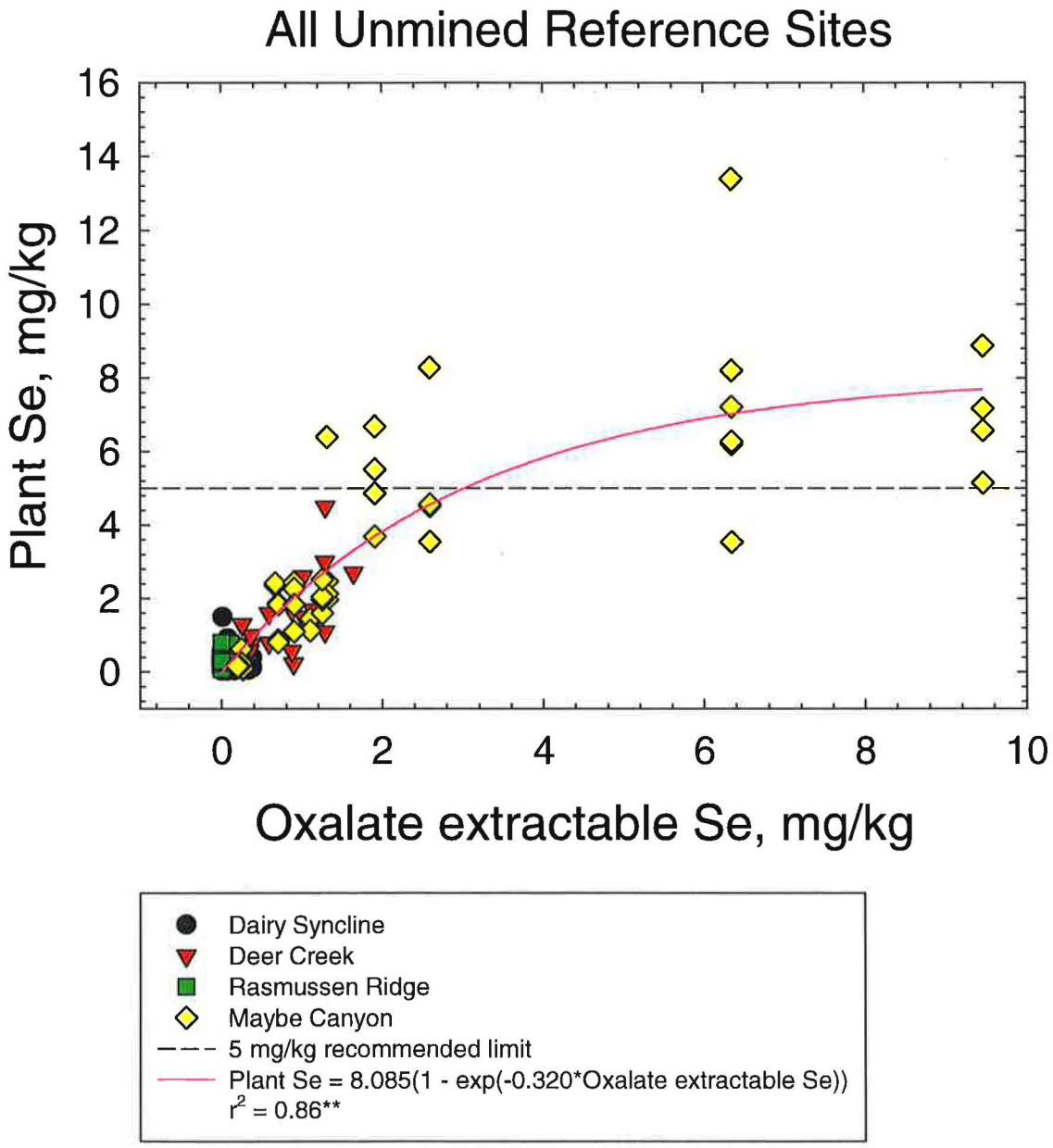


Fig. 34. Exponential model of the relationship between plant Se concentrations and soil oxalate-extractable Se along transects across sedimentary rock units (Wells limestone, Meade Peak phosphatic shale, and Rex chert) at Dairy Syncline, Deer Creek, Rasmussen Ridge, and Maybe Canyon.

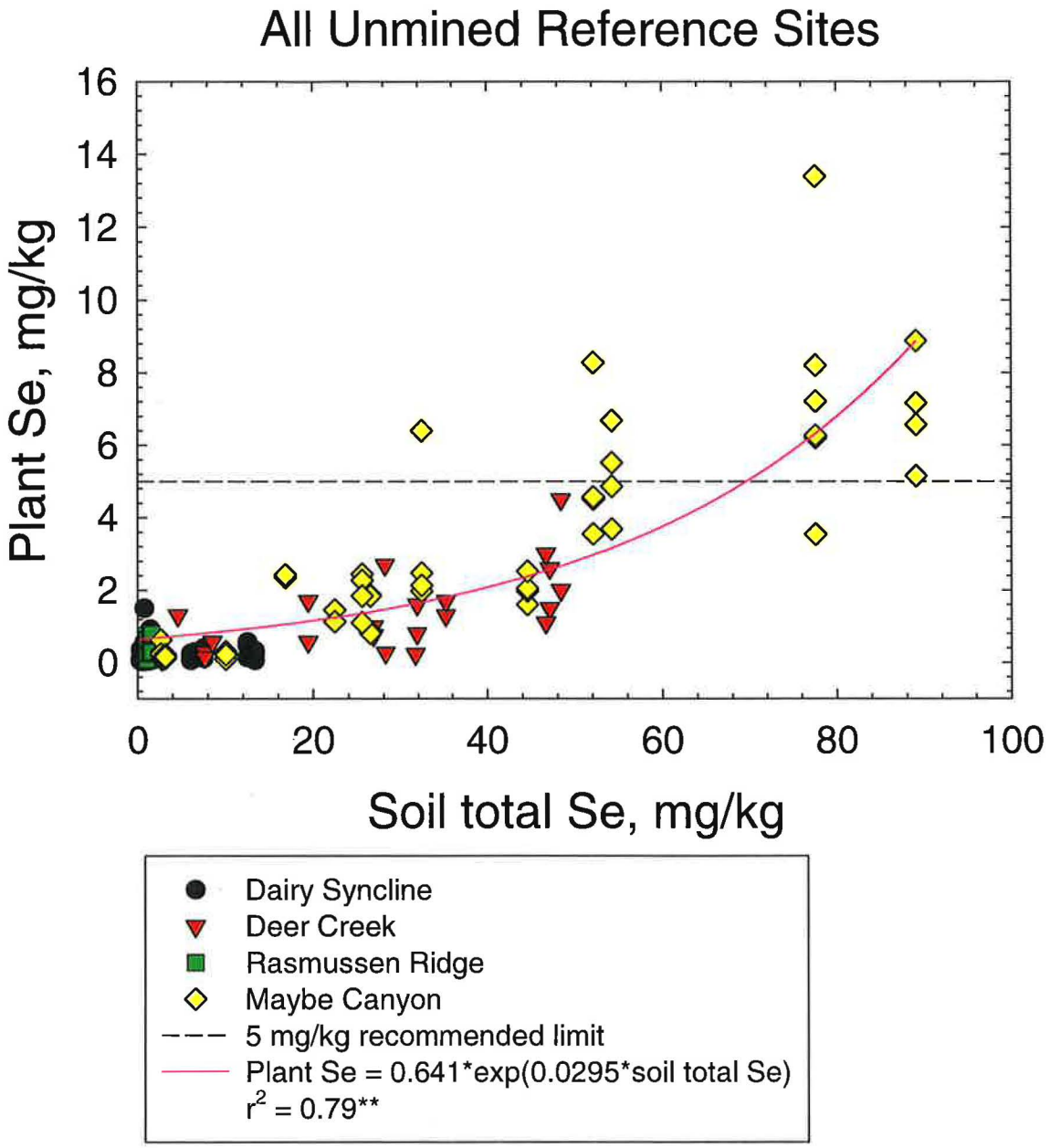


Fig. 35. Exponential model of the relationship between plant Se concentrations and soil total Se along transects across sedimentary rock units (Wells limestone, Meade Peak phosphatic shale, and Rex chert) at Dairy Syncline, Deer Creek, Rasmussen Ridge, and Maybe Canyon.

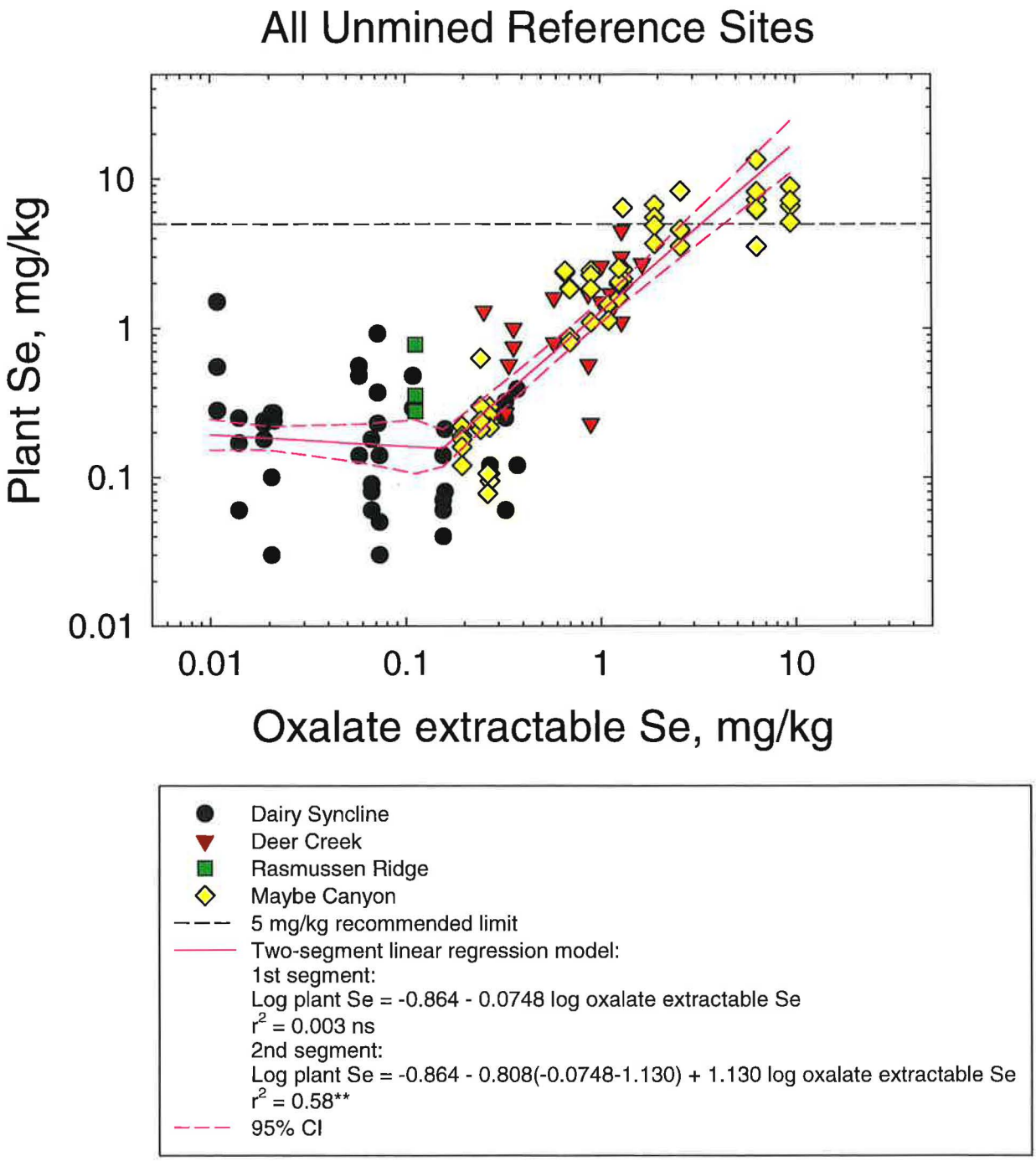


Fig. 36. Two-segment linear regression model relationship between plant Se concentrations and soil oxalate-extractable Se along transects across sedimentary rock units (Wells limestone, Meade Peak phosphatic shale, and Rex chert) at Dairy Syncline, Deer Creek, Rasmussen Ridge, and Maybe Canyon.

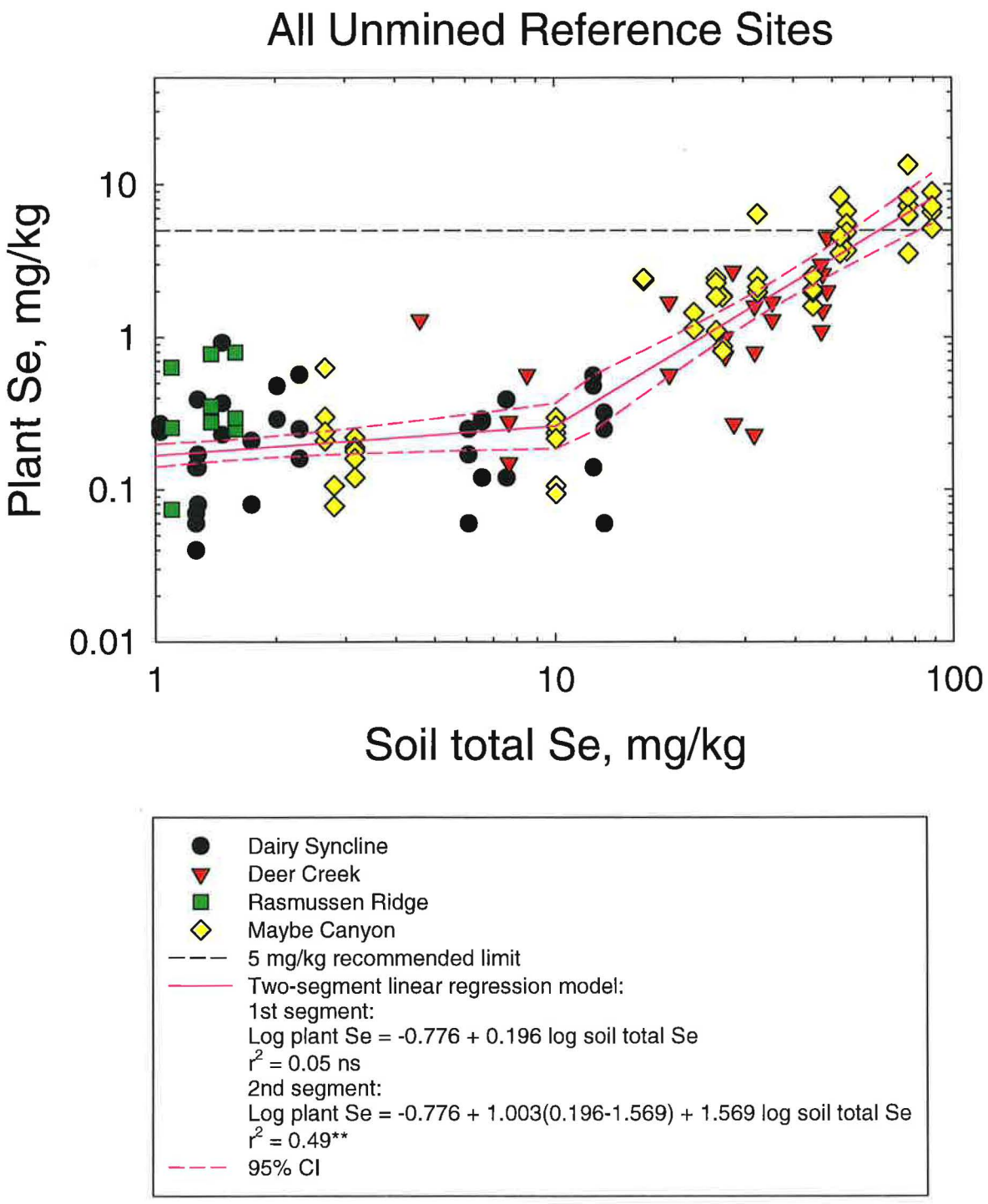


Fig. 37. Two-segment linear regression model relationship between plant Se concentrations and soil total Se along transects across sedimentary rock units (Wells limestone, Meade Peak phosphatic shale, and Rex chert) at Dairy Syncline, Deer Creek, Rasmussen Ridge, and Maybe Canyon.

Predicted oxalate-extractable Se levels associated with a 5 mg/kg recommended limit for plant Se for the various datasets and models are compared in table 3. Whether just the Maybe canyon data are used with an exponential model or all the unmined reference site data are used with exponential or two-segment linear regression models, an oxalate-extractable Se level of about 3 mg/kg (range of 2.8 to 3.3 depending on dataset and model) is predicted at 5 mg/kg Se in plants.

Predicted soil total Se levels associated with a 5 mg/kg recommended limit for plant Se for the various datasets and models are compared in table 4. Using a linear regression model for mean plant Se levels versus soil total Se for the Maybe Canyon data only, produces a predicted soil total Se level of 59 mg/kg at 5 mg/kg Se in plants. The exponential model predicts a soil total Se level of 70 mg/kg at 5 mg/kg of plant Se while the two-segment linear regression model predicts a soil total Se level of 66 mg/kg at 5 mg/kg plant Se.

Since these are model predictions, it is important to realize that some plants will have Se concentrations above the 5 mg/kg limit at lower soil oxalate-extractable and total Se levels as evidenced by the actual datapoints (Figs. 34, 35, 36, and 37). The most conservative limit for soil total Se would be set so that there is a negligibly small probability of having any Se concentrations above 5 mg/kg in plants growing in that soil. Since one aspen sample from the 2002 Maybe Canyon transect had a Se concentration of 6.4 mg/kg and was growing in a soil with 32.4 mg/kg total Se in the 0-10 cm layer, the most conservative recommended limit for total Se in undisturbed Phosphoria Formation soils would be below this level (32.4 mg/kg). The 1.5 mg/kg oxalate-extractable Se and 50 mg/kg total Se recommended limits from Fig. 33 represent a good compromise because they exclude many oxalate-extractable and total Se levels associated with higher plant Se concentrations (Figs. 34, 35, 36, and 37).

Table 3. Comparison of regression models for predicting soil oxalate-extractable Se levels associated with the 5 mg/kg recommended Se limit for forage plants.

Dataset	Regression model	Predicted soil total Se associated with 5 mg/kg plant Se
Maybe Canyon only	Exponential model: Plant Se = 7.761(1 – exp (-0.366 Soil oxalate-extractable Se)) r^2 = 0.97**	2.8 mg/kg
All unmined reference sites	Exponential model: Plant Se = 8.085(1 - exp(-0.320 Soil oxalate-extractable Se)) r^2 = 0.86**	3.0 mg/kg
All unmined reference sites	Two-segment linear regression model: log Plant Se = -0.864 - 0.808(-0.0748-1.130) + 1.130 log Soil total Se	3.3 mg/kg

Table 4. Comparison of regression models for predicting soil total Se levels associated with the 5 mg/kg recommended Se limit for forage plants.

Dataset	Regression model	Predicted soil total Se associated with 5 mg/kg plant Se
Maybe Canyon only	Linear regression model: Plant Se = -0.19 + 0.088 Soil total Se r^2 = 0.91**	59 mg/kg
All unmined reference sites	Exponential model: ln plant Se = -0.445 + 0.0295 Soil total Se r^2 = 0.79**	70 mg/kg
All unmined reference sites	Two-segment linear regression model: log Plant Se = -0.776 + 1.003(0.196-1.569) + 1.569 log Soil total Se	66 mg/kg

Factors influencing plant uptake of Se from Phosphoria Formation soils and sedimentary rocks:

Many factors affect plant uptake of Se including plant, soil, and environmental factors. These factors are interrelated and often not separable. Among plant factors, plant species, plant stage of development, and plant part (e.g., roots, shoots, leaves, seeds, etc.) are the principal factors that influence Se uptake. Environmental factors include temperature, precipitation, ambient light levels (e.g., photosynthetically active radiation), elevation, and aspect. Important soil properties include particle size distribution (i.e., sand silt, and clay), soil mineralogy (e.g., clay minerals, oxides, sulfides, etc.), soil pH and redox potential, soil solution composition, organic matter content, water content, depth to sedimentary rock parent material (rooting volume), total Se, and forms of soil Se.

The plant uptake and soil Se data from unmined reference sites illustrate the influence of some of these factors. Although there are some differences in Se uptake related to plant species and lifeform (Mackowiak et al. 2004), because soil total Se levels in unmined reference areas tend to be low compared to sedimentary rocks of the Phosphoria Formation and waste rock dumps (Herring and Grauch 2004, Amacher et al. 2001), plant uptake of Se tends to be low and therefore, differences in Se uptake among plant species and lifeforms tend to be less than an order of magnitude (e.g., Figs. 6, 7, 19, 20, 23, 28, 29, and 30).

Plant Se data from unmined reference areas and waste rock dumps combined with soil data illustrate some of the more important soil factors that influence Se uptake. These include:

- Total soil Se – Above a threshold level of total soil Se (approximately 10-15 mg/kg) in unmined Phosphoria Formation soils, plant uptake of Se increases linearly with increasing total soil Se on a log scale (Fig. 37). Below the threshold, plant uptake of Se is unrelated to soil total Se.

- Form of Se – Some forms of soil Se are more available for plant uptake than others. Phosphatic shales contain appreciable levels of water soluble Se (Herring 2004) and plant uptake is linearly related to available Se in phosphatic shale (Fig. 1). As soils develop in the Phosphoria Formation sedimentary rock parent material, total Se levels tend to decline with increased weathering (i.e., oxidation) (Fig. 2) and the residual Se in soils overlying the Phosphoria Formation contain less available Se than phosphatic shale as measured by oxalate extraction (Fig. 5). Plant uptake of Se increases linearly with increasing oxalate-extractable Se in unmined Phosphoria Formation soils above a threshold of approximately 0.2 mg/kg on a log scale (Fig. 36). Perhaps a field test for oxalate extractable Se could be developed to classify and segregate suitable and unsuitable soil capping materials for waste rock dumps without having to rely on more costly and time consuming plant uptake studies.

- Depth of soil – Deep, well-developed soils overlying the Phosphoria Formation have relatively low levels of Se compared to sedimentary rock parent material (e.g., Dry Valley (Mackowiak and Amacher 2003), Rasmussen Ridge (Fig. 23)). Some Phosphoria Formation soils have relatively high Se levels in the 0-10 cm surface layer and therefore, show higher levels of plant uptake (e.g., Maybe Canyon (Figs. 27, 28, and 29)).

- Weathering history (Table 1) – As previously discussed, once Phosphoria Formation sedimentary rock units are exposed to weathering, the more soluble forms of Se tend to be leached out, and less available residual forms of Se remain.

- Disturbance history (Table 1) – This is related to weathering history because as soils and sedimentary rock are disturbed by mining activities, they are subjected to increased oxidation and weathering, and thus Se mobilization potential and hence plant uptake increases (e.g., Fig. 3 and 2001 plant Se levels in partially disturbed exploration area at Maybe Canyon compared to 2002 plant Se levels in nearby undisturbed soil (Fig. 27)).

Recommendations:

The analysis of the relationships between plant and soil total Se in unmined reference areas leads to the following recommendations for use of Phosphoria Formation soils as capping materials for revegetation of waste rock dumps.

- Disturbed soils with total Se levels below 13 mg/kg are ok to use as waste rock dump caps without further testing (e.g., deep valley bottom soils (e.g., Dry Valley), deeper soils over the Meade Peak along ridges (e.g., Dairy Syncline lease area, Rasmussen Ridge))

- Soils with total Se levels above 50 mg/kg or oxalate-extractable Se levels above 1.5 mg/kg should never be used as waste rock dump caps (e.g., shallow soils

over the Meade Peak along ridges (e.g., unmined Maybe Canyon Phosphoria Formation soils) because even in an undisturbed state on the landscape, they have plant Se concentrations in excess of 5 mg/kg. At this time, we do not know the extent of soils with total Se levels above 50 mg/kg. They may comprise a relatively minor part of the Phosphoria Formation landscape.

- Undisturbed soils with total Se levels between 13 and 50 mg/kg should be tested for plant uptake of Se to determine if these are suitable for use as capping materials (see protocol in Mackowiak and Amacher 2004). Because these soils have not been tested after disturbance and their Se uptake properties remain unknown, prudence dictates a more thorough evaluation of these soils prior to use as soil caps.

- Consider blending high with low Se soils to bring the total Se level of the blended soil to less than 13 mg/kg.

References:

Amacher, M.C. 2003. Manual of Methods. 2003 edition. Open-file report on file at: USDA Forest Service Rocky Mountain Research Station, Logan, UT. 201 pp.

Amacher, M.C., J.R. Herring, and L.L. Stillings. 2001. Total recoverable selenium and other elements by HNO_3 and $HClO_4$ digestion and other soil characterization data from Wooley Valley Units 3 and 4 waste rock dumps and Dairy Syncline lease area soils, southeast Idaho. USGS Open-File Report 01-69. U.S. Geological Survey, Denver, CO. 65 pp.

Food and Nutrition Board. 1980. Recommended dietary allowances. Committee on Dietary Allowances, National Research Council, National Academy of Sciences. Washington, D.C. p. 162-164.

Herring, J.R. 2004. Rock leachate geochemistry of the Meade Peak phosphatic shale member of the Phosphoria Formation, southeast ID. p. 367-397. In: J.R. Hein (ed.). Life Cycle of the Phosphoria Formation: From Deposition to the Post-Mining Environment. Elsevier Science B.V., Amsterdam, The Netherlands.

Herring, J.R., and M.C. Amacher. 2001. Chemical compostion of plants growing on the Wooley Valley Phosphate Mine waste pile and on similar rocks in nearby Dairy Syncline, Caribou County, southeast Idaho. USGS Open-File Report 01-025. U.S. Geological Survey, Denver, CO. 47 pp.

Herring, J.R., and R.I. Grauch. 2004. Lithogeochemistry of the Meade Peak phosphatic shale member of the Phosphoria Formation, southeast Idaho. p. 321-366. In: J.R. Hein (ed.). Life Cycle of the Phosphoria Formation: From Deposition to the Post-Mining Environment. Elsevier Science B.V., Amsterdam, The Netherlands.

Herring, J.R., and S.A. Wilson. 2001. Phosphate shale analytical quality control materials of the USGS Western U.S. Phosphate Project – Bulk geochemical characterization and water leachate analysis. USGS Open-File Report 01-0024. U.S. Geological Survey, Denver, CO. 30 pp.

Jones, J.B. Jr. 1989. Soil testing and plant analysis laboratory manual. Benton Laboratories, Athens, GA. 78 pp.

Mackowiak, C.L., and M.C. Amacher. 2003. Plant uptake of selenium in phosphatic shale deposits and mine waste rock dumps. p. 136-148. In: J.W. Ellsworth (ed.). Proceedings of the Western Nutrient Management Conference. 6-7 March, 2003. Salt Lake City, UT. Potash and Phosphate Institute, Brookings, SD.

Mackowiak, C.L., and M.C. Amacher. 2004. Protocol for evaluating plant species for Se uptake potential and sedimentary waste rock and soils for Se bioavailability. Report prepared for ECAP/AML Project: Phosphate mining remediation feasibility studies. 11 pp.

Mackowiak, C.L., M.C. Amacher, J.O. Hall, J.R. Herring. 2004. Uptake of selenium and other contaminant elements into plants and implications for grazing animals in southeast Idaho. p. 527-555. In: J.R. Hein (ed.). Life Cycle of the Phosphoria Formation: From Deposition to the Post-Mining Environment. Elsevier Science B.V., Amsterdam, The Netherlands.

Perkins, R.B., and A.L. Foster. 2004. Mineral affinities and distribution of selenium and other trace elements in black shale and phosphorite of the Phosphoria Formation. p. 251-295. In: J.R. Hein (ed.). Life Cycle of the Phosphoria Formation: From Deposition to the Post-Mining Environment. Elsevier Science B.V., Amsterdam, The Netherlands.